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Method and device for a variable optical attenuator

Photonyx Ltd.

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Method and device for a variable optical attenuator.

1. Invention

The present invention relates to a device and a method, as well as uses thereof, for controlling the intensity of light in an optical fiber by use of a tunable dynamic grating.

2. Background

The demand for bandwidth for communication and information exchange has been growing exponentially. The growth has particularly accelerated by the introduction of Wavelength Division Multiplexing (WDM) technology used to multiplex optical signals along the same optical fiber by use of different wavelengths in narrow bands with minimal dissipation. Active components are needed in addition to the passive fibers, in order to generate, amplify, route, and filter signals. This has lead to the developed of a wide range of technologies to manipulate light in optical fibers, such optical components include filters, switches, amplifies, and attenuators. However, the high cost of components, in particular for the more advanced components including many subparts, are inhibiting the speed of deployment of optical systems, and the introduction of all optical networks. Consequently, it is necessary to develop cost effective components that have the necessary specifications, but allow low cost assembly and production method to be used.

A component of particular demand in fiber optical communication systems is the variable optical attenuator. Attenuators are used as stand-along components for example to compensate for aging effects in other components, and to avoid saturation of detectors. However, for a more dynamic network structures, such as in an all-optical network, the signal strengths in the system from various sources or from various pathways will vary widely, and the need for reconfigurable or dynamic variable optical attenuators arise. Variable optical attenuators are also an important subpart of modules such as equalizers and optical add/drop multiplexers. For such applications, it is particularly the scalability of the technology that will determine the end price of the module, and this is also the main advantage of the presented invention.

The following list of patents constitutes the prior art in this field: GP 2 265 024 - Geoffry Martland Proudly -15.09.1993 – A spatial light modulator assembly, US 3,835,346 - Fred Mast et. al - 10.09.1974 - Cathode Ray Tube, US 5,867,301 - Graig D. Engle - 02.02.1999 – Phase Modulating Device, US 4,879,602 - 07.11.1989 - William E. Glenn et. al – Electrode Patterns for Solid State Light Modulator, US 5, 116,674 – 26.05.1992 – Beat Schmidhalter et. al – Composite Structure, US 5,221,747 – 22.06.1993 – Gerald R. Goe et. al – Improved Process and Catalyst for the Preparation of 2,2`Bipyrdilys, US 4,529,620 – 16.07.1985 – William E. Glenn - Method of Making Deformable Light Modulator Structure, US 4,857,978 – 15.08.1989 – Efim Goldburt et. al – Solid State Light Modulator Incorporating Metallized Gel and Method of Metallization, US 4,900,136 – 13.02.1990 – Efim Goldburt et. al – Method of Mettalizing Silica-Containing Gel and Solid State Light Modulator Incorporating the Metallized Gel, WO 99/09440 – 25.02.1999 – Foster Miller Inc. – Switchable Optical Components.

Several realizations have been suggested for tunable diffraction gratings with applications to fiber optical components. The most promising technology is diffractive MEMS (D-MEMS). This technology as fronted by for example LightConnect and Silicon Light Machines. The technology is based on a moveable diffraction grating consisting of at least two separate pieces. A stationary reflective bottom, and a moveable set of thins blades, the grating, made of etched silicon. The blades can be moved up and down by the application of an appropriate electrical field. The result is a diffraction grating, where the effective phase shift of the grating is given by the relative position of the blades and the reflective surface below. This allows the grating to be turned on and off with

a response time of only a few milliseconds. However, the voltages required to displace the blades are still high, on the order of tens to hundreds of Volts. This technology can be used to make effective variable optical attenuators, but the set of blades must be processed out of silicon. This is an expensive process, and the yield of the process goes dramatically down as the system size is increased. Components made from D-MEMS are hence effective, but expensive. The presented technology aims to take the advantage of the D-MEMS technology, the use of diffractive optics, and combine it with the best of other technologies, such as LCD, which is easier to manufacture.

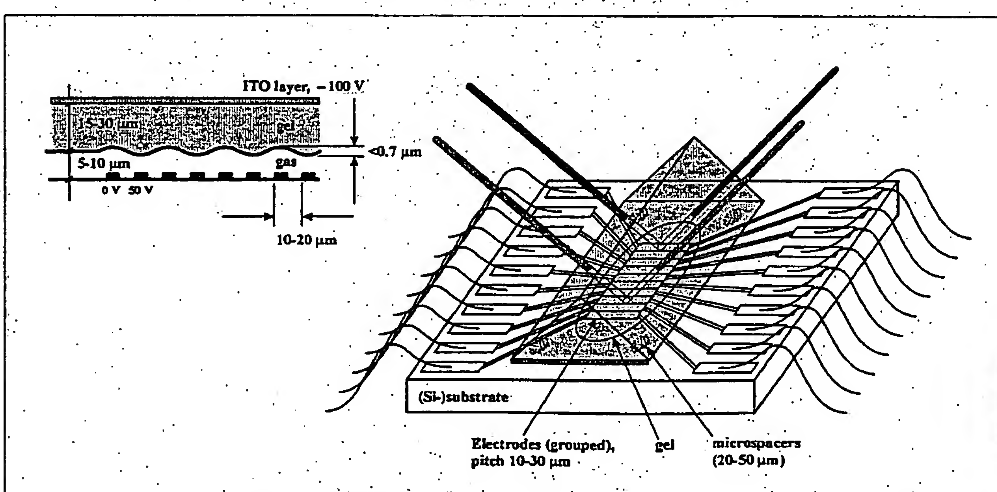
3. Tuneable Diffraction Grating Technology

The present invention aims to have the performance of D-MEMS but with the ease of manufacturing found in LCD or LCOS technologies. The technology is based on tuneable surface diffraction gratings. Such gratings have been disclosed in the literature and in patents. For example, our preferred embodiment is based on the technology described in articles and books published by Guscho in Russia. However, the technology can also be based on modulators with surface coatings, as described by Engle (US 5,867,301). The basic technology of these modulators are well known, and have been used for projection applications since the introduction of the Eidophor project almost 50 years ago. However, for projection applications, the contrast for the light on the screen is important. Consequently, these applications have relied on using the light in the 1st and the 2nd diffraction orders. For applications in fiber optical components, the light in the 0th order is used instead. The technology allows the light in the 0th order to be tuned continuously from full intensity to an attenuation of 20dB, or even more for multi-pass configurations. With a combination of driver electronics, and optical solutions to send the light into and collect the light from the modulators, this invention demonstrates that tuneable surface diffraction gratings may be used for applications such as variable optical attenuators.

3.1. Modulator design

3.1.1. Modulator principles

The technology is based on light diffraction due to surface modulation in a thin gel layer. The basic modulator design and principles are shown in figure 1. The modulator consists of a thin laye of gel attached to a transparent prism. The gel has been index matched to the prism glass, and the gel has low light absorption in both the visible and the infrared range (less than 2% for a typical system). Typically, the gel layer is 5-40 micrometers thick. Electrodes are processed on a flat substrate layer separated from the gel surface by a thin air gap (5-10 micrometers thick). Fibres may be used as spacer material for the manually assembled test samples.



A bias voltage is applied across the gel and the air gap. Our current working hypothesis is that this results in charges accumulating on the gel surface. As a result a net force is acting on the gel surface due to the electric field. In addition each signal electrode is possible to individually address. By applying a local signal voltage, forces are applied to the gel surface, resulting in a surface modulation. The elastic surface response is rapid, with a response time of tens of microseconds. However, various charging and relaxation processes also occur on longer time scales in the gel, resulting in a slow drift in the surface modulation in the range from microseconds to minutes. Some form of feedback is therefore necessary for stable operation.

The typical dimension of the current test modulator's active area (electrodes) is 3mm x 6mm (yellow area on figure 2). The electrodes are placed as interlacing combs with 125 line pairs/mm as the current maximum resolution. The resolution limit is due to the high precision necessary for the low gel thickness and narrow air gap which are necessary for high density of surface modulation. A periodic variation of driving voltages produces an approximately sinusoidal modulation with the same period as for the voltages. Typical values for the bias and the driving voltages on the electrodes are 100 V.

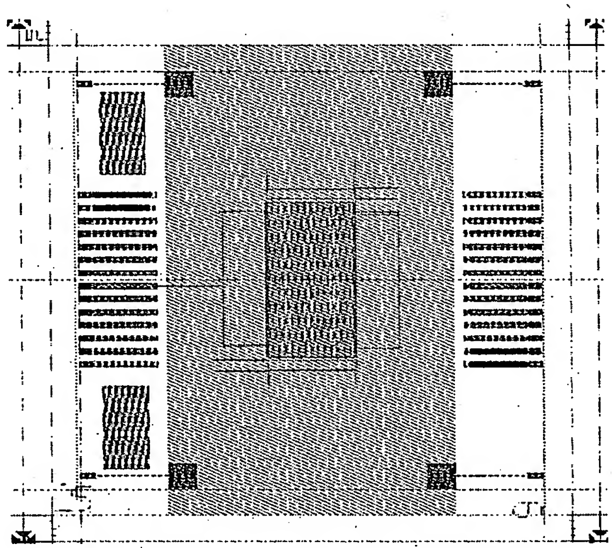


Figure 2. Layout of the silicon substrate for test modulator. Note that several electrodes are grouped into one bond pad on this layout.

When light is reflected off the modulated surface the modulator acts as a diffraction grating. To reduce polarization effects and transmission losses, a conical diffraction setup has to be used for high line densities. The incoming direction of the light beam is parallel to the electrode lines and the corresponding grooves of the surface modulation. The result is that the light is diffracted into higher diffraction orders.

Figure 3 shows the intensity in the 0^{th}, 1^{st}, and 2^{nd} diffraction orders based on theoretical calculations. The intensity is wavelength dependent, and to first order the phase shift is proportional to a/λ, where a is the amplitude of the surface modulation and λ is the wavelength of the light. The variation of wavelength of the C-band will typically give a variation of attenuation of

1%. This means the best zero level for an off switch will be worse than 1% over the whole C band. By varying the surface modulation amplitude, the attenuation of the 0^{th} order can be varied continuously. For 1550 nm light, a surface modulation amplitude of 300nm is needed to reach full attenuation in the 0^{th} order. As can be seen from figure 3, the maximum intensity in the 1^{st} order at full attenuation in 0^{th} order is approximately 30% (for one of the maxima).

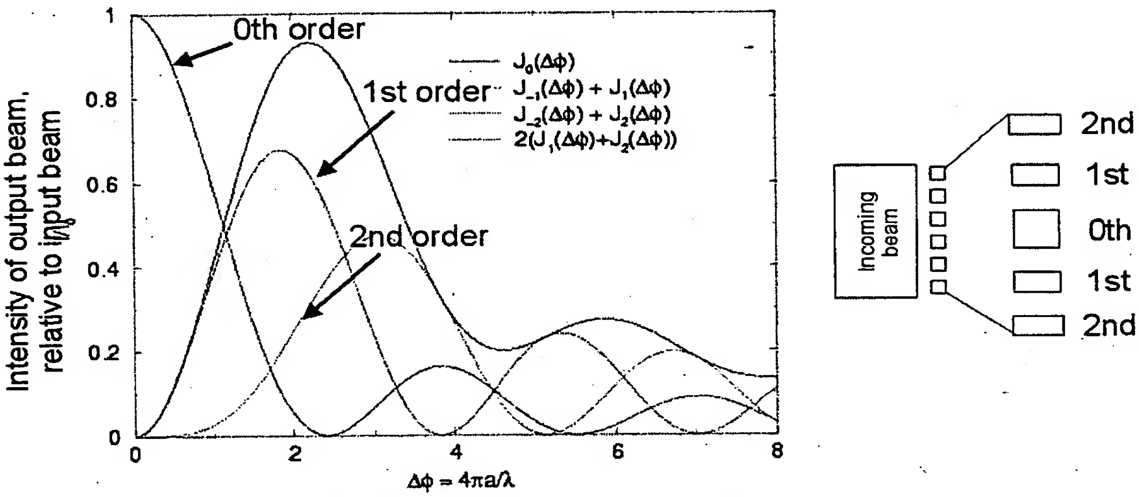


Figure 3: Intensities in the 0^{th}, 1^{st}, 2^{nd}, and the sum of the 1^{st} and the 2^{nd} orders.

3.2. Theoretical Calculations of VOA Behavior

3.2.1. <u>Operating principles and functions</u>

The gel modulator is a programmable diffraction grating. The grating consists of a sinusoidal gel relief with variable amplitude. An electric field generated by electrodes controls the amplitude of the gel, and the spacing between the electrodes gives the period of the grating. The modulator is a reflection grating and has an incidence angle of 45° (see figure 3.1).

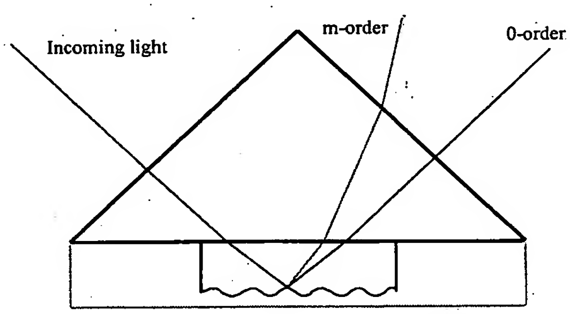


Figure 3.1: Side-view of the amplitude relief modulator

Depending on the orientation of the incoming light beam, the diffraction can be conical or in-plane diffraction.

Configuration 1: Conical diffraction

Conical diffraction occurs when the prism top is perpendicular to the electrode lines. Figure 3.2 shows the intensity of different diffraction orders as a function of gel relief amplitude. The period of the grating is 8 micrometers, which corresponds to 125 lines/mm.

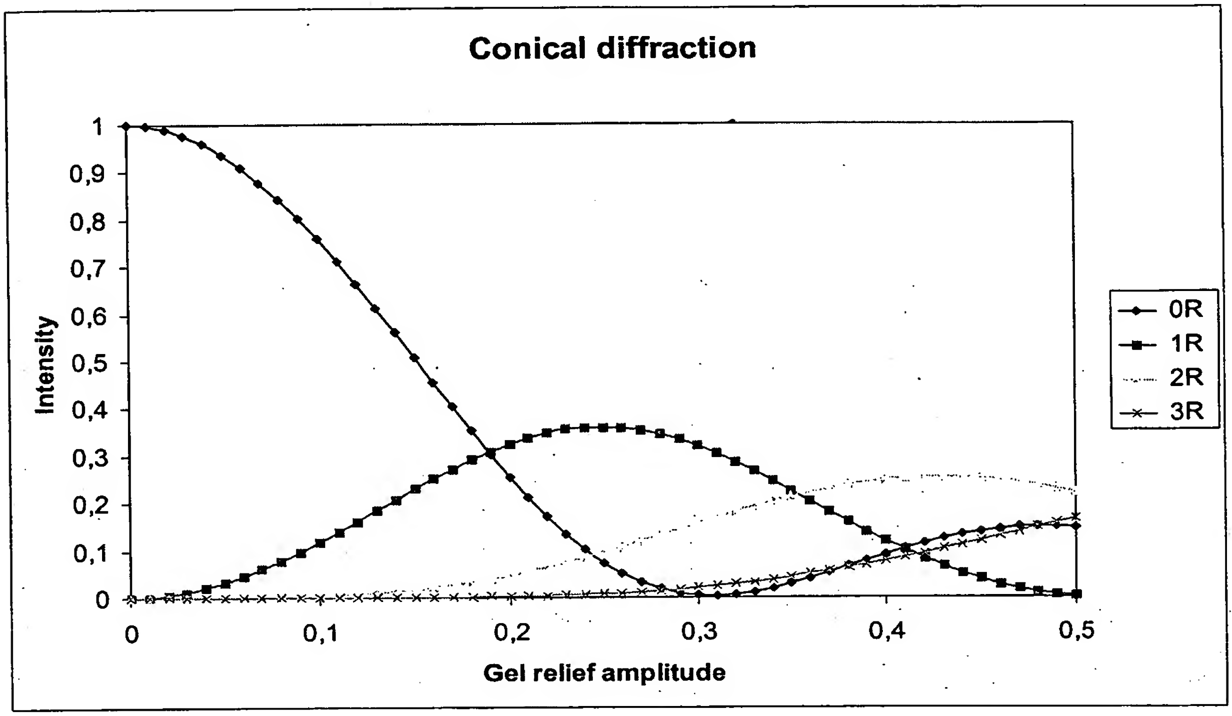


Figure3.2: Intensity of different diffraction orders as a function of gel relief amplitude The period of the grating is 8 micrometers, which corresponds to 125 lines/mm.

Advantages with conical diffraction:

- All light will be reflected by the grating, and no light will be transmitted through the gel.
- This configuration is less dependent on the polarisation of the incoming light.
- The 0[th] order can be reduced to very close to zero.

Disadvantages with conical diffraction:

- The orientation of the diffraction orders is not on a straight line; instead they form a conical distribution. This may make a modulator with conical diffraction harder to design and assemble.
- The positive and negative diffraction orders are symmetrical. An asymmetrical behaviour will give higher intensity in some orders.

Configuration 2: Oblique in-plane diffraction

Oblique in-plane diffraction occurs when the prism top is parallel to the electrode lines. Figure 3.3 shows the intensity in different diffraction orders as a function of gel relief amplitude. The period of the grating is 8 microns, which corresponds to 125 lines/mm.

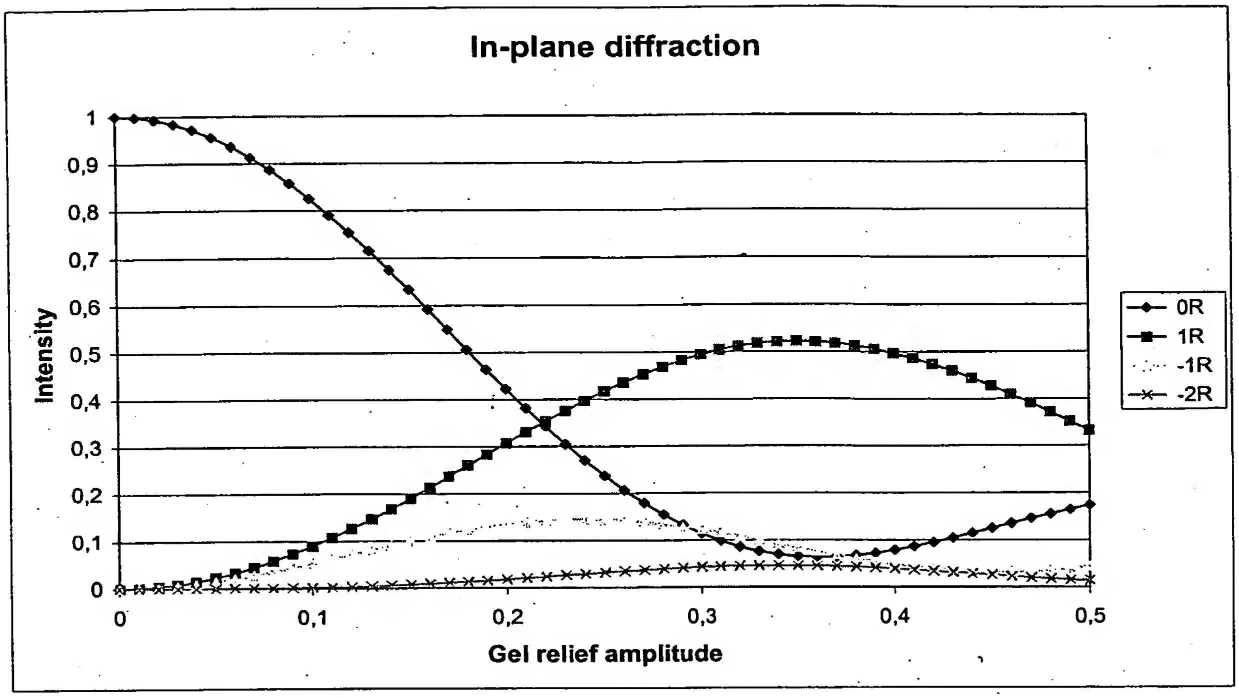


Figure 3.3: Intensity in different diffraction orders as a function of gel relief amplitude. The period of the grating is 8 microns, which corresponds to 125 lines/mm.

Advantages with in-plane diffraction:

- The orientation of the diffraction orders is on a straight line. This makes a modulator with in-plane diffraction easy to design and assemble.
- The positive and negative diffraction orders are asymmetrical. An asymmetrical behaviour will give higher intensity in some orders, which may be more efficient for a switch device.

Disadvantages with in-plane diffraction:

- Some light will be transmitted through the gel. The transmission is dependent on the gel relief amplitude. At 0.35 micrometers, where the 0^{th} order is at a minimum, the transmission will be 26%.
- The 0^{th} order will not reach zero. The lowest intensity is about 0.07, which is also polarisation dependent.
- This configuration is more dependent on the polarisation of the incoming light. The intensity of each order is different. Figure 3.4 shows the polarisation dependence of the 0^{th} order for linearly polarised light.

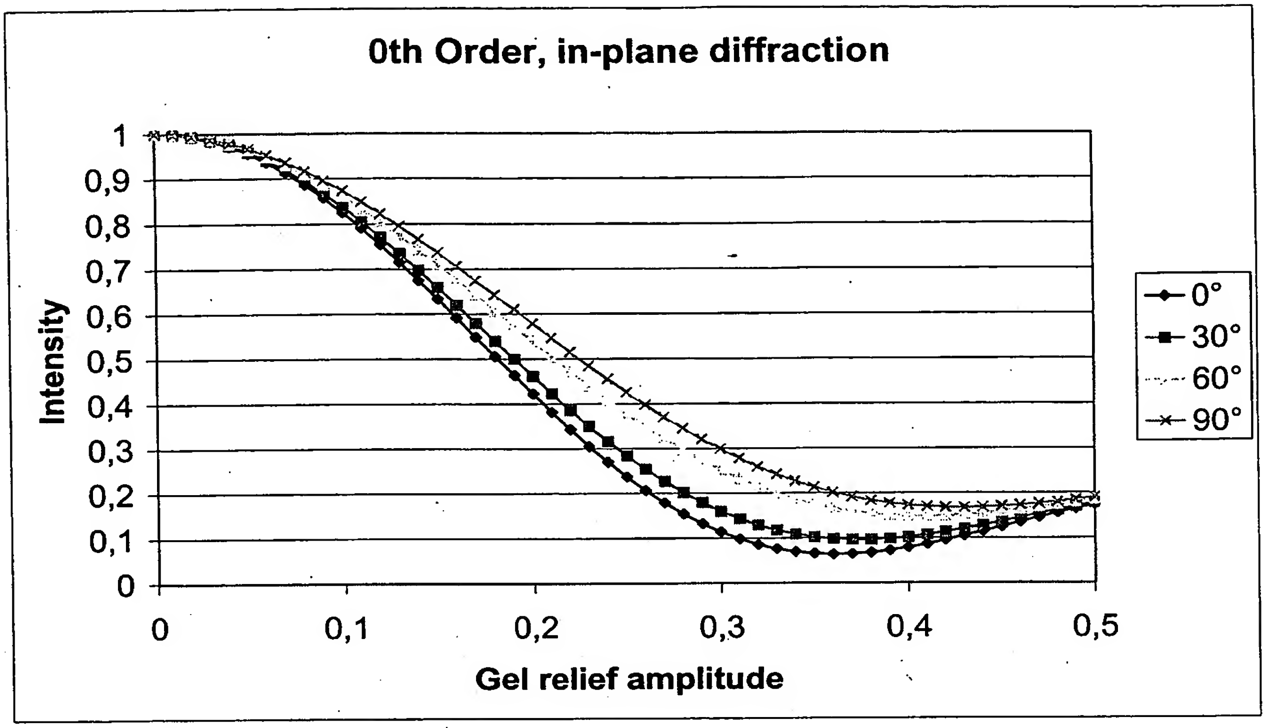


Figure 3.4: Polarisation dependence of attenuation in the 0^{th} order for in-plane diffraction.

3.2.2. Performance evaluation

- *Modulator with 125 l/mm and conical diffraction*

For practical reasons, this modulator was the main candidate for the demonstration.
Assumptions:

$n_{prism} = 1,45$
Wavelength = 1554 mn

Order -2 to 2

Diffraction Orders (m)		-2	-1	0	1	2
Diffraction angles inside the prism	ϕ	20.8	10.7	0	10.7	20.8
(degrees from the 0:th order)	θ	4.1	1.0	0	1.0	4.1
Diffraction angle outside the prism	ϕ	30.9	15.6	0	15.6	30.9
(degrees from the 0:th order)	θ	6.0	1.5	0	1.5	6.0

If the prism is 5mm high and 10mm wide, following distances can be measured on the prism facet:
Distance between 0.th and 1:st order is 0.67mm.
Distance between 1:st and 2:nd order is 0.70mm.

- *Modulator with blazed grating*

If the gel relief is changed from a sinusoidal shape to a skew triangular shape, new diffraction properties occur.

A grating with a skew triangular shape is called a blazed grating. In a blazed grating almost all light will be distributed between the 0^{th} and a specific diffraction order. With these characteristics the modulator can work as a switch. The following figure shows the intensity of each diffraction order as a function of the gel relief thickness.

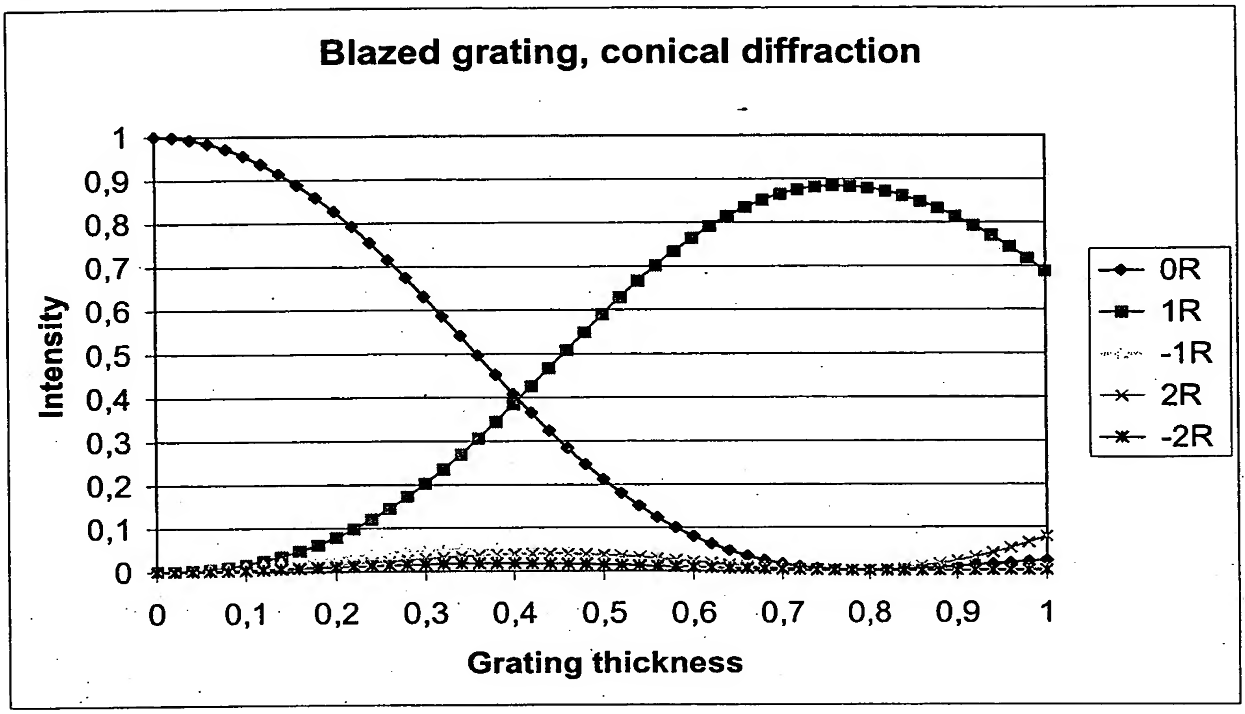


Figure 3.5:Intensity in each diffraction order as a function of the gel relief thickness.

3.2.3. <u>Driving modes</u>

A problem that occurs when driving the modulator is a memory effect. The gel gets caught in its shape if its stays for a long time. To get rid of the memory effect, different approaches can be used:

- Alternating mode

The electrodes are configured so that every other has a voltage and every other is grounded. A sinusoidal grating period is created by one grounded electrode and one with voltage. By inverting the configuration in a periodical way it is possible to get rid of the memory effects. However, during the switching time the light sent trough the modulator cannot be controlled, and a telecom application must be able to manage light information all the time.

- Rolling alternating mode

The rolling alternating mode will only switch between the two different driving voltages at a few places at one time. Information can continuously be sent through the modulator. A problem that may arise is that a phase shift will occur in the modulated grating just where the voltage switch is placed. The light signal output will depend on where in the grating the moving phase shift is located.

- Static mode with feedback

In a static driving mode a memory effect will occur. But if a feedback controlling system is used, the driving signal can be compensated for the memory effect. If this is possible for all kinds of memory effects, it will be the best suitable driving mode for telecom applications.

3.2.4. Summary

The Photonyx gel technology is an advanced material platform that has the potential to generate several electrically tuneable telecom products. To comply with requirements from telecom applications, conical diffraction (low insertion loss, low polarisation dependant loss) and static driving mode with feedback (high accuracy, no data loss) are preferred operating modes.
Three core functions can possibly be implemented with this technology: light modulation, spectral filtering and optical switching.

3.3. Variable Optical Attenuator Demonstrator Description

Two basic types of VOA demonstrator applications have been tested. The two applications are described in the following.

3.3.1. Demonstrator based on 125l/mm substrates

The following functions have been selected for the demonstrator:

- variable attenuation
- variable coupler / tapper (switch)
- spectral selectivity / filter
- monitoring (feedback)

The proposed demonstrator is an array of 2 attenuators with on-chip monitoring functions. It would include two incoming fibres and 4 outgoing fibres (see figure below). The +1 and –1 orders could be used as tapers to deflect a limited part of the energy to monitor the power in each incoming channel. Spectral selectivity could also be demonstrated by using the angular selectivity of collimating optics.

Feedback from the +1 and –1 orders could also be used to increase the attenuation range and optimise accuracy.

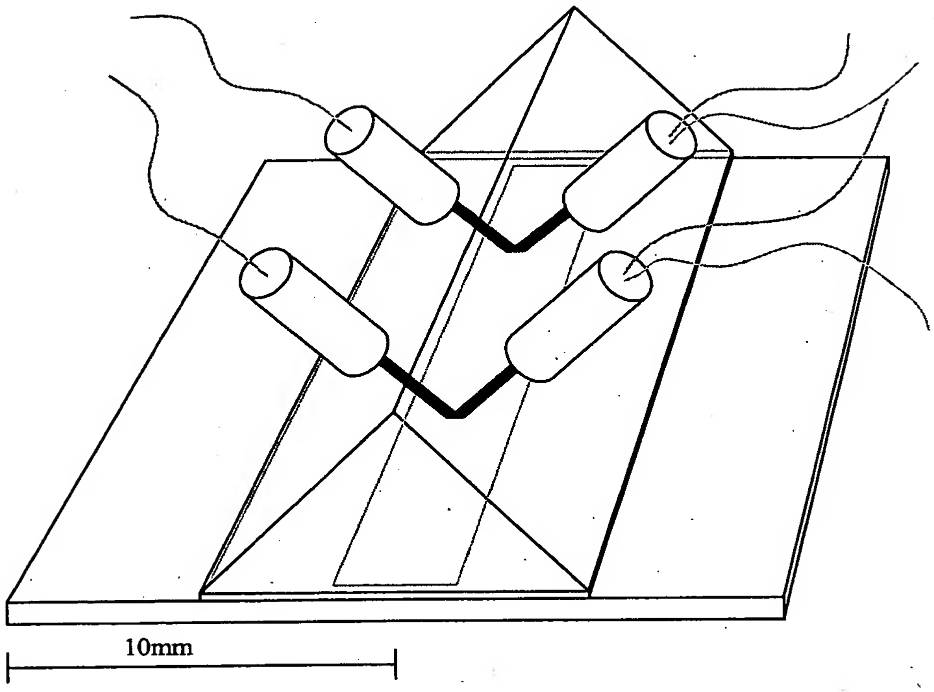


Figure 5.1: Sketch of the proposed demonstrator (125l/mm)

3.3.2. Demonstrator based on 33 l/mm substrates

33 l/mm substrates may be simpler and cheaper to manufacture, and should therefore alse be considered. In such a case, the very small angular separation of the diffracted beams makes the practical fabrication of 4 fibre-couple outputs extremely difficult. Therefore, the proposed "33 l/mm " demonstrator is based on two input and two output channels, neglecting higher diffraction orders. The demonstrator would be made of:

- A modulator, with the possibility to control the gel relief for two channels.
- A programmable control electronics board to control the attenuation levels of both channels with a feedback loop.

A functional sketch of the demonstrator is provided in figure 5.2.

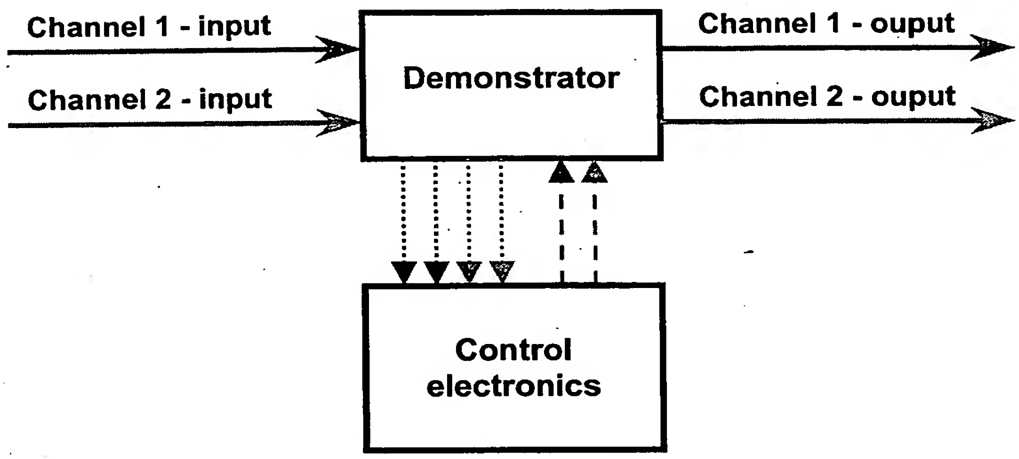


Figure 5.2: Sketch of the proposed demonstrator (33 l/mm)

Two photodetectors per channel will provide information on optical power level at the input and at the output of the modulator. The control electronics will use this information to optimise the voltage levels applied to the gel in order to accurately attenuate the signals in both channels according to a nominal value.

Two main scenarios are proposed:

1. *Variable optical attenuator*

Two main functions are required:

- The user defines an output value of the *optical power* for each channel. The control electronics optimises the voltage levels to attenuate the signal until the required *optical power* level has been obtained.

Example: P_{in} (channel 1)=12mW, P_{in} (channel 2)=10mW

User settings: P_{out} (channel 1)=6mW, P_{out} (channel 2)=0.1mW

The modulator and control electronics attenuate both signals until the user settings have been reached, i.e. 6mW in the 1st channel and 0.1mW in the second channel. The values from the two output photodiodes are used for optimisation in the feedback loop.

- The user defines an output value of the *attenuation* for each channel. The control electronics optimises the voltage levels to attenuate the signal until the required *attenuation* level has been obtained.

Example: P_{in} (channel 1)=12mW, P_{in} (channel 2)=10mW

User settings: attenuation (channel 1)=3dB, attenuation (channel 1)=20dB

The modulator and control electronics attenuate both signals until the user settings have been reached, i.e. 6mW in the 1st channel and 0.1mW in the second channel. The ratios of the values given by the input and output photodiodes in each channel are used for optimisation in the feedback loop.

2. Dynamic channel equalisation

This demonstration is intended to provide some insights about the capacity of Photonyx modulator to perform dynamic gain equalisation.

Two channels, with varying intensities over time, are sent to the system. The demonstrator dynamically identifies and attenuates the channel with highest optical power until both channels are equalised. Equalisation is performed within 1ms.

Finally, it might be useful to connect the two channels in series to demonstrate higher attenuation range.

3.4. Experimental Characterization of the VOA

The built VOA demonstrators have been tested, in order to determine insertion losses, polarization dependent losses (PDL), and other specifications relevant for fiber optical components for telecommunication.

3.4.1. Insertion loss on the modulator without gluing

Insertion loss at no voltage:
The insertion loss was between 0.16 and 0.30dB. This gives a PDL of 0.14dB. The PDL is received by twisting the fiber for the incoming light to get all states of polarization (SOP). If the fiber with the outgoing light is twisted, nothing happens because of the detector has no PDL.

The insertion loss was tested at different places on the active area and the variation was small, also the PDL had very small variations.

The collimators where then placed in a skew incidence angle, about 1.5 degrees. The insertion loss was between 0.18 and 0.35dB, the PDL was 0.17 dB. A skew angle of 1.5 degrees is much in this context and the difference in PDL is small.

PDL at about 15dB attenuation:
The fiber was twisted to find out the PDL around 15dB. Max signal was 14.4 and min 15.9. This gives a PDL equal to 1.5dB, which corresponds well with theoretical results.

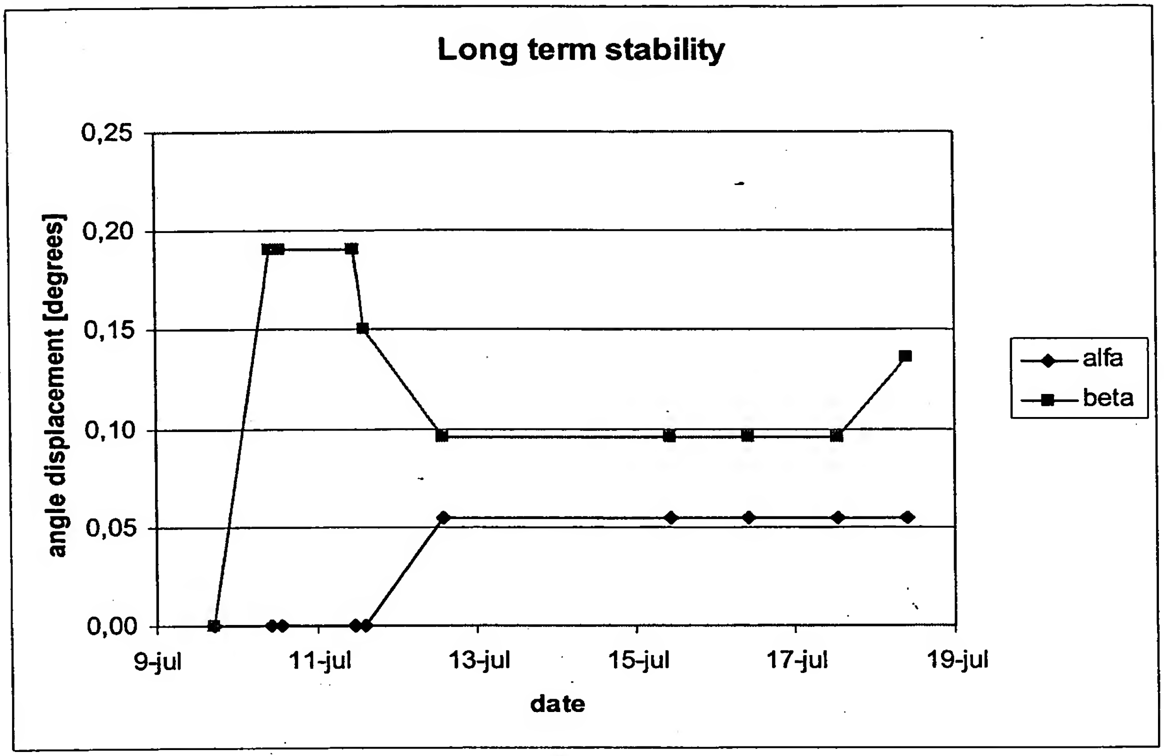
3.4.2. Insertion loss for the prism only

Insertion loss
The insertion loss for the prism without the gel was measured to be max 0.097 and min 0.074dB, this gives a PDL of 0.022

3.4.3. Long term stability test of the glued collimators

Test 1 Stability test for the glue
Two input channels were glued to one side of a not mounted prism and the output beam was projected onto a wall at a distance of 4.4 meters. A paper was placed on the wall and the movements of the two spots were plotted. A reference beam from a third collimator (side by side

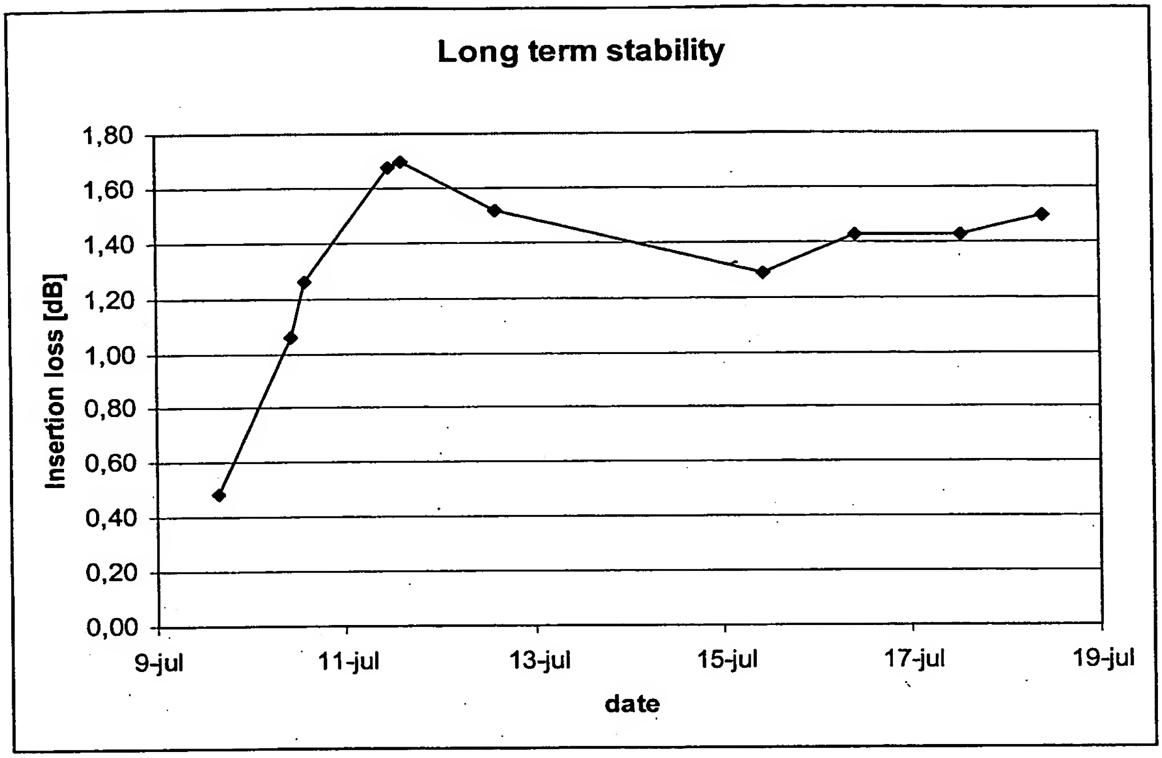
with the glued ones) was used as reference to compensate for any movement of the optical table. The movements of the glued collimators is shown in the plot below:



The angular movement of the glued collimators is larger in collimator beta, the maximum angular displacement is 0.19 degrees. According to the experiment " Angular and spatial dependence of the collimator coupling efficiency" 0.19 degrees is enough to give an insertion loss of 13dB. The conclusion is that the gluing procedure is not stable enough.

Test 2 Insertion loss test with no voltage

One channel (two collimators) was glued on the T1024 modulator with an insertion loss of 0.49dB without driver box. The modulator was fixed in a measurement set-up where all fibers were fixed with tape to maintain the SOP. 10 insertion loss measurements were then done during 9 days. Signal or bias voltage was never turned on. The graph below show the result:

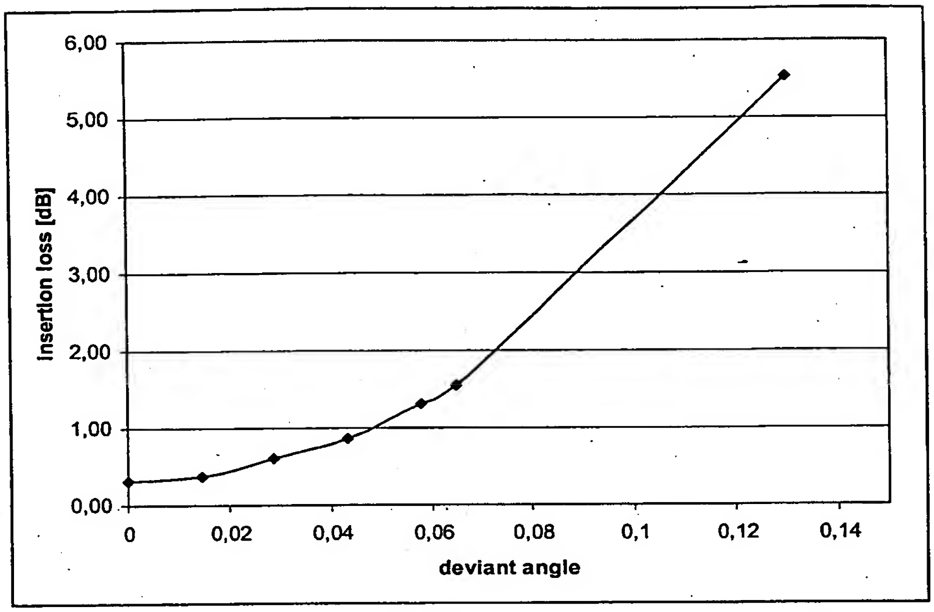


The insertion loss is increasing from 0.49 to maximum 1.69dB. The insertion loss seems to stabilise around 1.40dB that corresponds to an angular deviation of 0.06 degrees of one of the collimators. The conclusion is that the gluing procedure is not stable enough.

3.4.4. Angular and spatial dependence of the collimator coupling efficiency

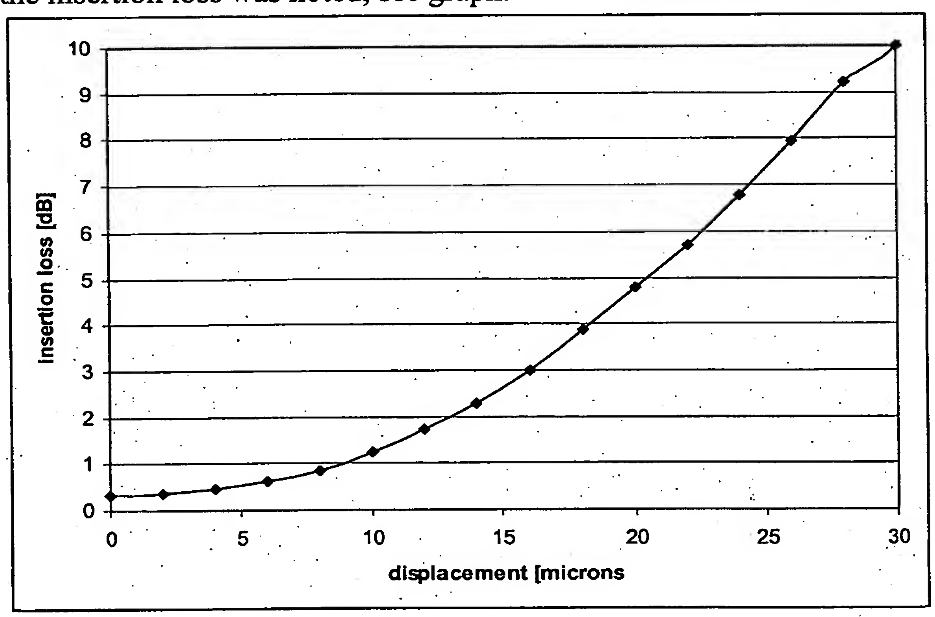
To get a connection between test 1 and test 2 in "Long term stability test of the glued collimators" two more measurements was done. A modulator, T1025, and two collimators was mounted but not glued and the lowest insertion lost was found. After that, the angle and position of one of the collimators was changed and the insertion loss was noted.

In the first experiment the angle of one of the collimators was slightly changed and the insertion loss was noted, see following graphs:



The inserton loss as a function of the deviant angle of one of the collimators

In the second experiment the spatial position of one of the collimators was slightly changed and the insertion loss was noted, see graph:



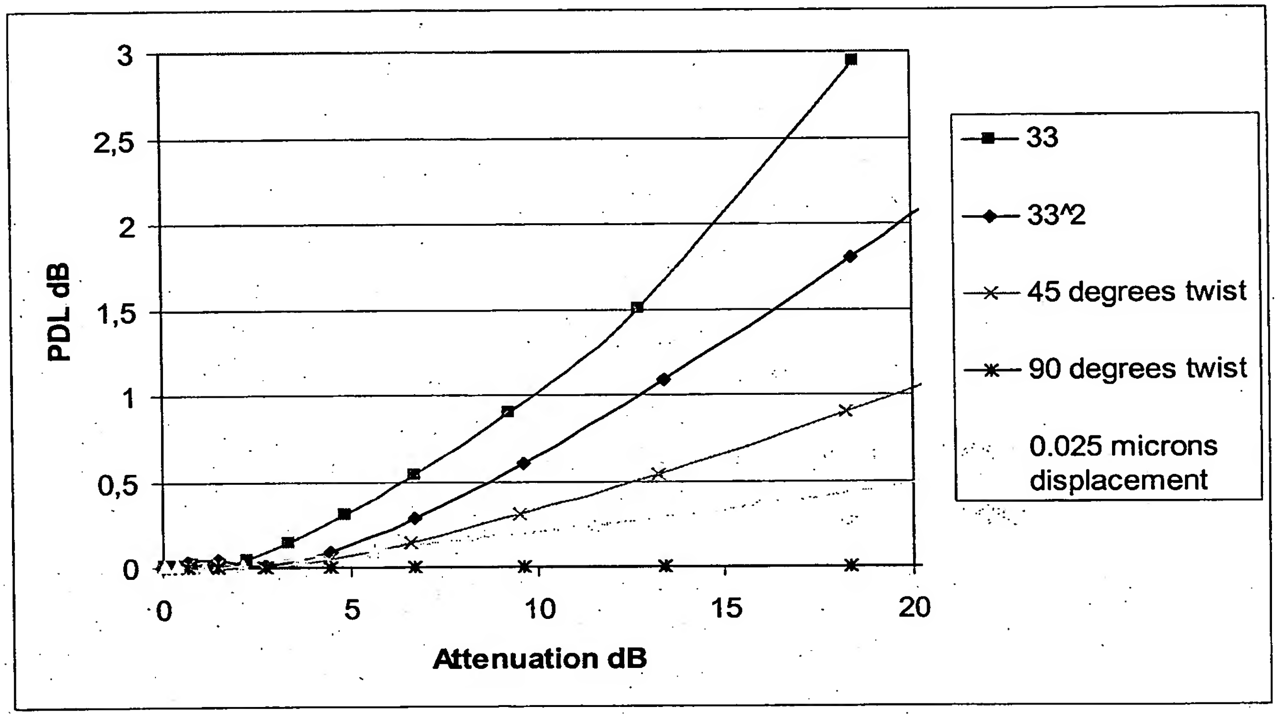
The inserton loss as a function of the spatial displecement of one of the collimators

The conclusion of these experiments is that the collimators is very sensitive for angular and spacial movements. To maintain an insertion loss lower than 1dB, the deviant angle must be smaller than 0.04 degrees and the spatial displacement must be smaller than 8 micrometers.

3.5. Polarization dependent losses: solutions

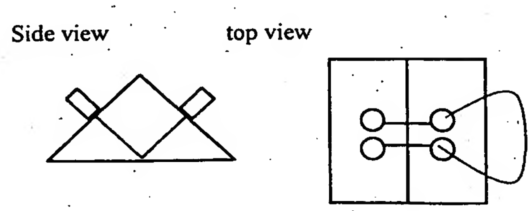
The measured values of PDL is slightly high for some applications. As a result several double or multi-pass configurations were developed to counteract the PDL. The effect of introduction double or multi-pass configuration for PDL has been calculated theoretically, as illustrated in the following plot:

The expected (simulated) PDL will reach 0.1dB at 3dB attenuation range and 0.5dB at 6dB attenuation range. The double pass PDL will reach at maximum 0.1dB at 4.5dB attenuation range and 0.5dB at 9dB attenuation range according to simulations. But the PDL for the double pass can be even lower if the polarisation is 90° twisted in the fibre between the two channels.



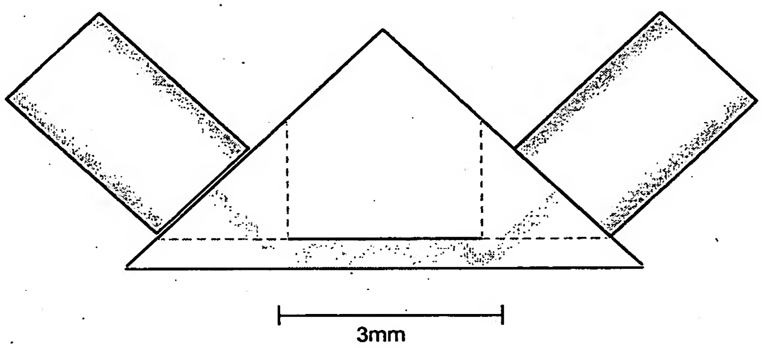
Grating Solver simulation

There are two conceptual ways to use a multipass configuration for the modulator. The first way is to pick up the 0^{th} order after the first diffraction and then let this order be diffracted one more time. The output will be the square of the 0^{th} order intensity. This gives the opportunity to get a very high attenuation. To be able to pick up only the 0^{th} order a lens or collimator must be used to get the Fraunhofer approximation. The sketch below shows a double pass configuration:



A double pass configuration using the Fraunhofer approximation, a fiber is used to connect the two-collimator pairs.

The other way to do a multipass configuration is to mirror back the diffracted beam and diffract it again. In this case is the distance between the two diffractions very close and the Fresnel approximation is used. With this kind of configuration the total phase shift will be the sum of all phase shifts that occurs when the light beam is hitting the diffraction pattern. If the beam is hitting the diffraction pattern n times the gel amplitude must be n times lower and approximately the electrical field must be n times smaller.



Sketch of a Fresnel multiple-pass configuration with mounted collimators. The beam is 0,4mm, the collimators are 2.8 mm in diameter and the glass thickness where the multipass is located is 0.7 mm.

3.6. Electronic design of the VOA system

This section deals with the requirements for the driver electronics needed to build the complete VOA demonstrator.

3.6.1. Demonstrator overview

The VOA demonstrator will be able to demonstrate the 3 following features:

1) 2 channel fixed attenuation setting
2) 2 channel fixed power setting
3) 1 channel serial coupled, high attenuation setting

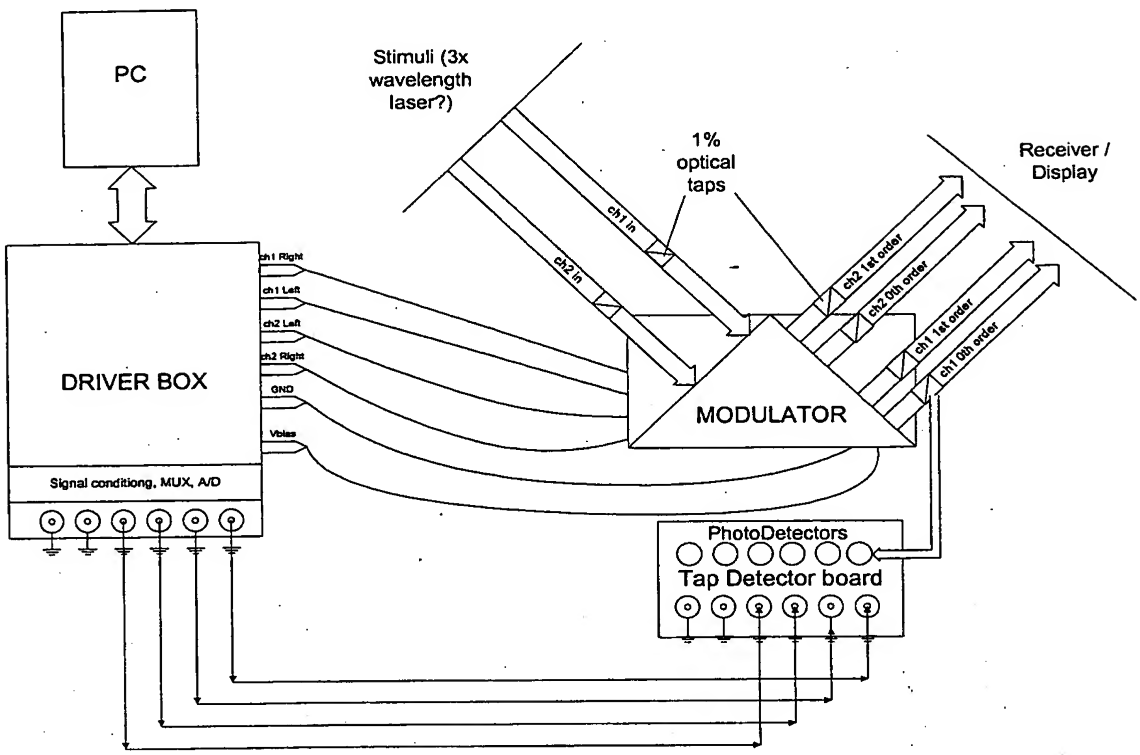


Fig 1. System drawing. Note that the 1st orders will not be used in the VOA demonstrator, but are intended for switching applications, or use of this order as direct feedback. Our VOA will employ taps on the 0^{th} order output for the feedback signal.

Main subparts list:

Part	Type
Stimuli & Receiver equipment	tbd
Substrates	33 l/mm TELLUS02
Gel	Pt-based
Prism	custom design (WZW ?)
Collimators and fibres	Koncent 2,8mm/0,45 mm/xxx(tbc)
PCB with photo detectors	Fermionics FD300 or AME (tbc)
Feedback taps	Koncent 1% / 99% (tbc)
PC & Driver box	custom

3.6.2. Driver requirements

The driver shall consist of one custom hardware box, containing all analog, digital, power and PC communication components. Necessary net adapters shall NOT be integrated into the box.

The pcb sizes should aim at single Europe standard (100x160mm), and if several pcb's are to be designed, they must be stackable using piggyback connectors. Hence the target for the total box

size is 110x170x50mm. These measures may be increased in order to fit into a practical and available box.

3.6.3. Hardware interface requirements

Parameter	Min	Typ	Max	Unit
Number of driver outputs	4			
Driver output range	250	-	300	V
Driver output accuracy		0,5		%FS
Driver output step size	5	1		V
Driver output slew rate	5	20	300	V/μs
Driver bandwidth	1		10	kHz
Driver max current (short cct. protection)		10		mA
Vbias range	-300		0	V
Vbias step size		10		V
Vbias accuracy		1		%FS
Vbias max current (short cct. protection)		10		mA
Analog inputs	6			
Analog input sample speed	10			kHz
Analog input range		tbd		

3.6.4. Control requirements

Signal driving

The signal driving shall be possible to use in two modes, with and without feedback.

With feedback

The target is input from user, being one of the following:

1) attenuation level in dB (based on known ratio between 2 feedback sensors)
2) output intensity (from photo detectors)

The feedback loop shall typically have 1ms response time. The feedback algorithm must be easy to change, as it will be subject for optimizations after the driver box has been made.

Without feedback

In this mode, there is only a voltage setting of the four channels. The update from the GUI to the hardware should triggered by a "send" button or similar.

It must be possible to define 2 periods, with one voltage for each period (per channel). The periods may individually be set, in the range 50μs – 5 seconds, giving a possible frequency range on the output signal between 0,1Hz and 10kHz., and also any frequency in between, with a very dynamic duty cycle.

This mode will make the driver suitable for most cases of single ended driving as well as alternating mode driving.

Having (a lot) more than 2 timing periods would make the driver box very generic, and suitable for making more sophisticated waveforms (ref. our 100V signal generator in the lab), but this is not required initially.

VBias

A) The VBias voltage must be settable by the user. There is only one bias voltage for both optical channels.

Data Storage

This feature has a slightly lower priority, and is concerned with the possibility to define sampling of relevant status and analog input channels (Photo detector signals, feedback driving voltages etc.). It is possible to think of filtering views, but an initial function to just stream all data to an ASCII file will be sufficient

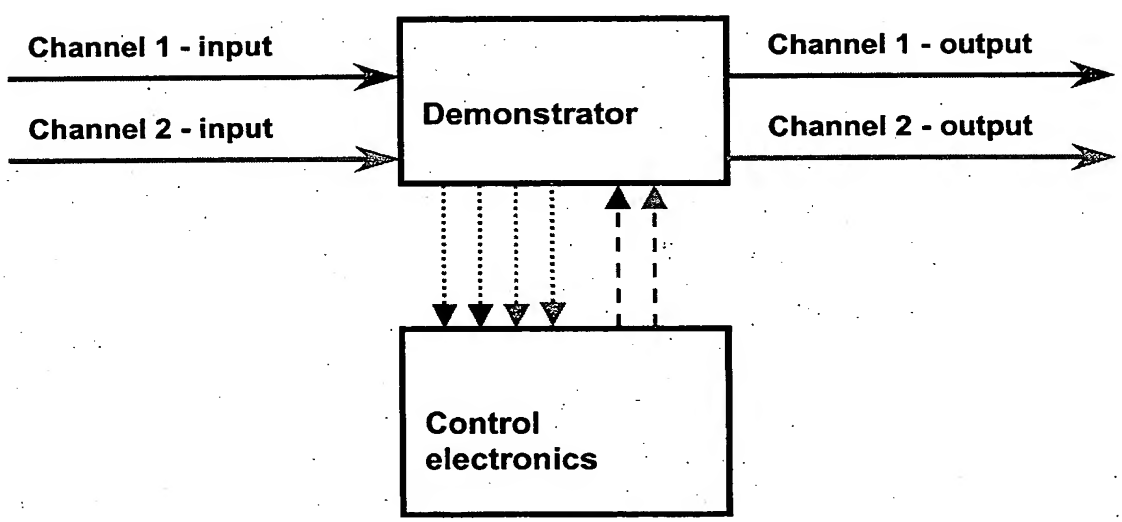
3.7. Optical design of the VOA system

3.7.1. Introduction

This document provides an overview of the optical design information for building a 2-channel VOA demonstrator. ion. This design specification is only for a demonstrator, not for production and many of the components, (collimators, glue, Fiber couplers and detectors) are off-the-shelf components.

The sketch below shows the function of the demonstrator:

Two photodetectors per channel will provide information on optical power level at the input and at the output of the modulator. The control electronics will use this information to optimise the voltage levels applied to the gel in order to accurately attenuate the signals in both channels according to a nominal value.



Schematic drawing of the 2 channel VOA demonstrator

The demonstrator design can be split up into two parts: optical design and electronic design.

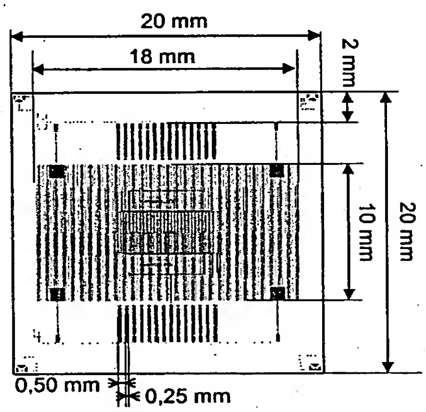
The optical part of the modulator can be split up into substrate, prism, collimators, glue, fiber couplers and detectors. The design of each part is described in the following sections. Many of the design parameters, like the Return loss or insertion loss, are dependent of several parts in the system.

3.7.2. Substrate

The available substrate is the 33 lines/mm. With this substrate, the angular separation between the 0^{th} and the 1^{st} order will be about 3 degrees inside the prism. 3 degrees will be enough to avoid crosstalk and give enough attenuation range with the chosen collimators. Higher resolution will give a larger angular separation between the orders, it will also affect the PDL.

The available active area size is 3x6 mm. This is enough for a two-channel with the chosen collimators. A larger area will give lower crosstalk and the possibility to have more channels but will affect the production yield.

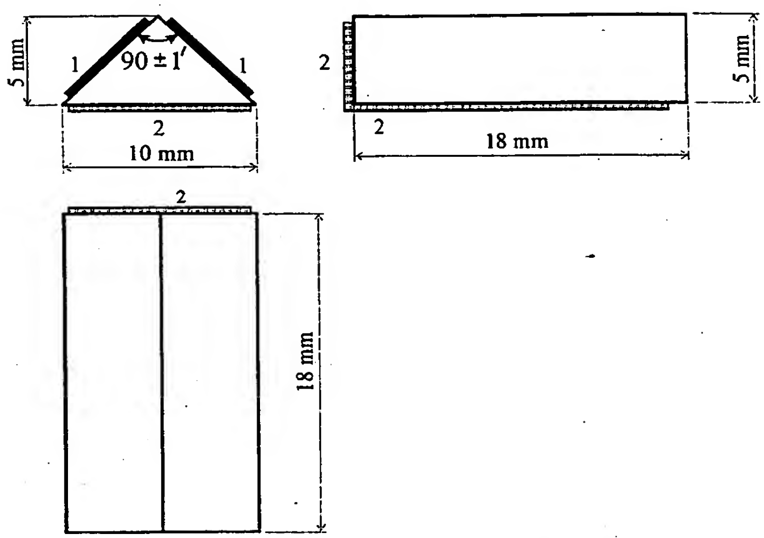
Grating pitch	33lines/mm
Active area	3x6mm



3.7.3. Prism

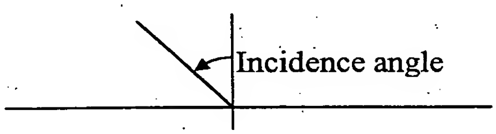
The Prism size is 10x5x18 mm. It is placed over the substrate to give conical diffraction. Conical diffraction is used to get smaller PDL and also to get higher attenuation. The prism size gives an optical path of 10mm, which is within the standard for collimators.

The prism size is also tested for gel deposition, spacing and gluing on the substrate and it also fits the 20x20mm substrate well.



Dimensions of the prism.

The prism angle is set to 90 degrees, which gives an incidence angle of 45degrees in the prism and 47 degrees in the gel. The angle is optimised to be just at the limit of total internal diffraction. Larger angle (higher prism) requires higher gel relief amplitude and smaller angle (lower prism) gives transmittance through the gel.



The definition of incidence angle

The prism refractive index is 1.444 for 1550nm; the gel index is about 1.4. The index miss match gives a reflectance of about 33 dB in the 0^{th} order. This reflectance is much smaller than the attenuation range specification and therefore acceptable.

Size	10x5x18mm
Prism top angle	90 degrees
Refractive index	1.444

3.7.4. Collimators

To get the light from the fiber to be a much larger well-collimated free-space beam some kind of lens are needed. In this case a gradient index (GRIN) lens is used. Because of the GRIN lens is flat-ended, it is easy to mount it on the glass prism. The collimator has a working distance of 10mm; this corresponds to the optical path through the prism. The size of the chosen GRIN lens, with the fiber pigtail, is 9mm long, and 2.8 mm in diameter, the refractive index of the lens is around 1.57. The return loss is about 55-60dB between the collimator and the glue. This is obtained by still having the AR coating for air on the collimator surface. The acceptance angle of the collimator is 0.15 degrees; this angle gives low enough crosstalk according to standard specifications.

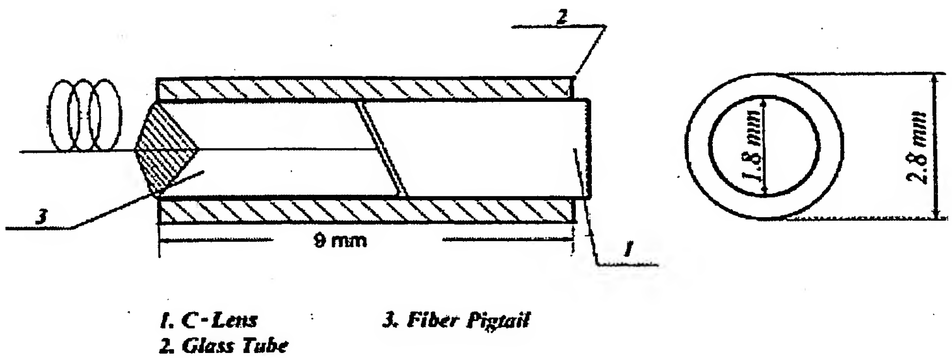


Image from [www.koncent.com]

Collimator type	Koncent KFC-A-900-1550-N-10-G
Size	9x2.8mm
Refractive index	~1.57
Working distance	10mm
Central Wavelength	1550nm
Spectral bandwidth	60nm
Insertion loss	0.07 to 0.18dB
Acceptance angle	0.15degrees
Beam diameter	0.45mm
Beam divergence	0.25 degrees

3.7.5. Glue

The glue is used to fix the collimators on the prism. The glue must be index matched with the prism and the collimators to fulfil the return loss specification and have a good transmittance for 1550nm to lower the insertion loss. The thermal expansion is higher than the expansion of the prism but the demo is only designed for Lab environment The chosen glue is an UV hardening epoxy glue.

Glue type	Epotek OG142
Refractive index	1.5871
Thermal expansion up to 116 °C	$58x10^6$ in/in/°C
Shore D Hardness	86

3.7.6. Fiber couplers

Fiber couplers are used to tap 1% of the light for power measurement before and after the modulator. For a 2-channel VOA 4 taps are used.

Coupler type	Koncent SWC-P-900-1550-1-01-1
Dimension	ϕ3.0x52mm
Insertion loss	0.12/19.8dB
PDL	0.05

3.7.7. Detectors

The detectors are used to do power measurement of the 1% taped light from the fiber coupler.

The power of a standard optical metro network is about 13dBm to -28dBm. The power range of the detectors must be that range but 20dB lower because of the 1% tap. This gives an optical power range of -7 to -48dBm for the detectors.

The chosen detectors have a power range of -55 to 13dBm.

Detector type	FCI-InGaAs-100L-FC
Power range	-55 to 13dBm

3.8. Feedback control

When a gel modulator is subject to an excitation voltage, a wave pattern on the gel surface is set up, which is used to deflect or attenuate optical signals. When the excitation voltage is removed, the gel will not immediately return to the initial state. This phenomenon is called memory effect.

The result of memory effect is that there will not be a predictable relation between the attenuation achieved and the applied excitation voltage in a VOA application of the gel modulator.

Therefore the measured attenuation level of the VOA is used as a feedback signal for controlling the excitation voltage of the modulator.

The feedback system is shown in figure 1.

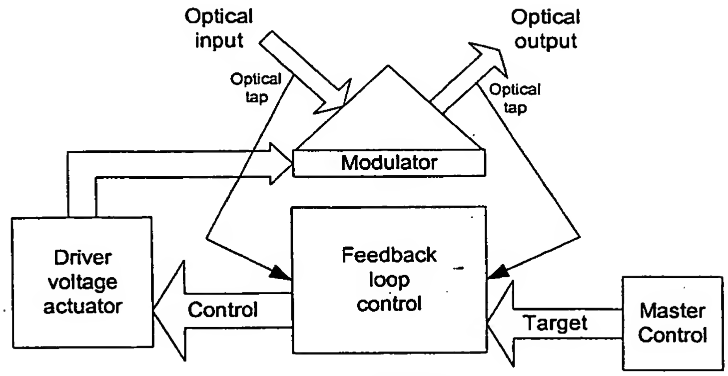


Figure 1

The master control unit supplies the attenuation target value to the feedback control unit. The optical input and output are measured, and the feedback loop control unit measures the attenuation of the modulator. This attenuation value is compared to the target value, giving a correction signal. The driver voltage is adjusted based on this correction signal.

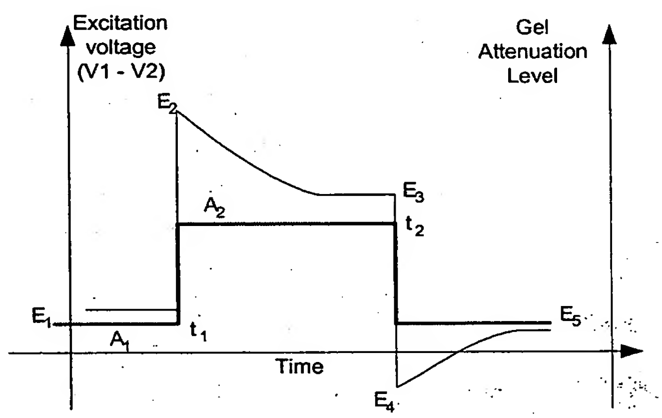


Figure 2

A typical operation sequence is shown in Figure 2.

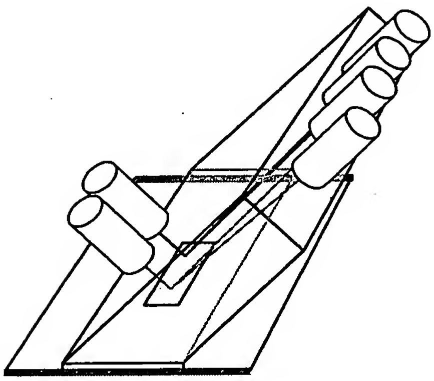
The left-hand axis shows the voltage difference between the excitation electrodes $E = V1 - V2$. The right-hand axis shows the gel attenuation level A. Initially, the attenuation is A_1, with a steady-state excitation voltage of E_1. At t_1 the master control unit receives a new target level A_2. The feedback control unit adjusts the excitation voltage to E_2 to achieve the new target value. Due to the memory effect in the gel, the excitation voltage will over time drop to a steady-state level E_3 At t_2, the master control unit switches the target value back to A_1. Due to the memory effect, the feedback reduces the excitation voltage to E_4. E_4 may be negative, indicating that the V2 electrode is positive with respect to the V1 electrode. After some time, the excitation voltage will approach a steady-state value E_5.

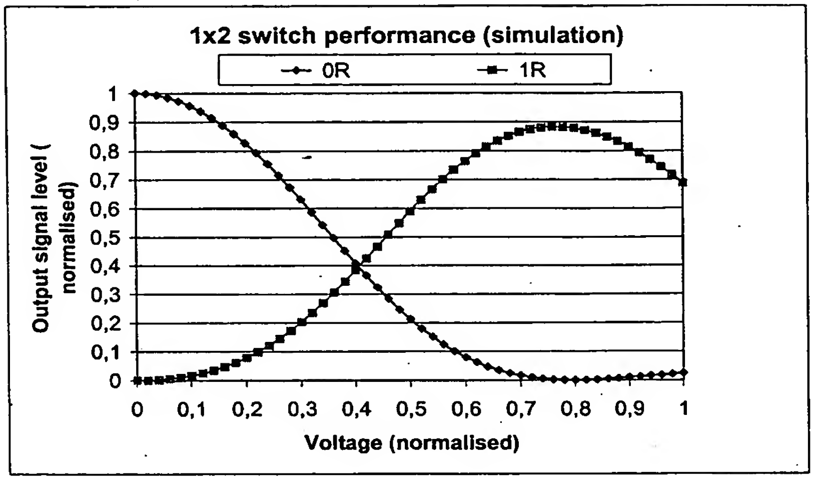
3.9. Other applications

3.9.1. <u>1x2 switch</u>

A simple 1x2 switch may be realised by fixing collimators at the 0^{th} and at one of the 1^{st} order positions. By switching the grating on and off, the light will be switched from one position to the

other. (By tuning the amplitude, this could also serve as a variable tap). A sketch of a possible demonstrator is shown below:





However, based on the intensity distribution of the different diffraction orders of a sinusoidal grating, a modulator with conical geometry will have maximum intensity of one of the first orders at about 30%, and this is not when the 0^{th} order is at the minima.

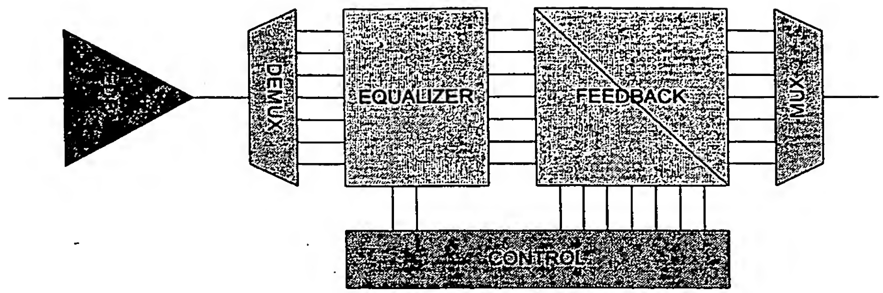
Forming a blazed grating, gives the possibility of improving these characteristics dramatically, with up to 90% efficiency in the selected 1^{st} order (ref simulations plot above). We are currently doing some experiments to characterise the actual efficiency of blazed gratings. Assuming we can reach an acceptable performance, we want to pursue this design further.

A second assumption, is that we can achieve this performance on modulators with a line density of about 75-125 l/mm), in order to be able to use practical prism and collimator sizes. (The sketch above is to scale for a working 33 l/mm test modulator and 1.8 mm collimators. The prism size is not ideal).

3.9.2. Dynamic Gain Equalizer

A channel equalizer, or a gain flattening device, can be made as a combination of a free-space demux and a VOA array. A key challenge is to reduce the required number of optical components. We are therefore working on integrated (hybrid) designs. Since the modulator (without collimator optics for each channel) has a low marginal cost per added channel, combined free-space solutions may provide cost-effective components.

The channel equalizer consists of the VOA element in combination with a demux element, such as a diffraction grating or a thin film filter, which disperses the optical signal so that individual wavelengths are separated in space. An example illustration of the DGE element with the VOA element integrated is shown in the following illustration.

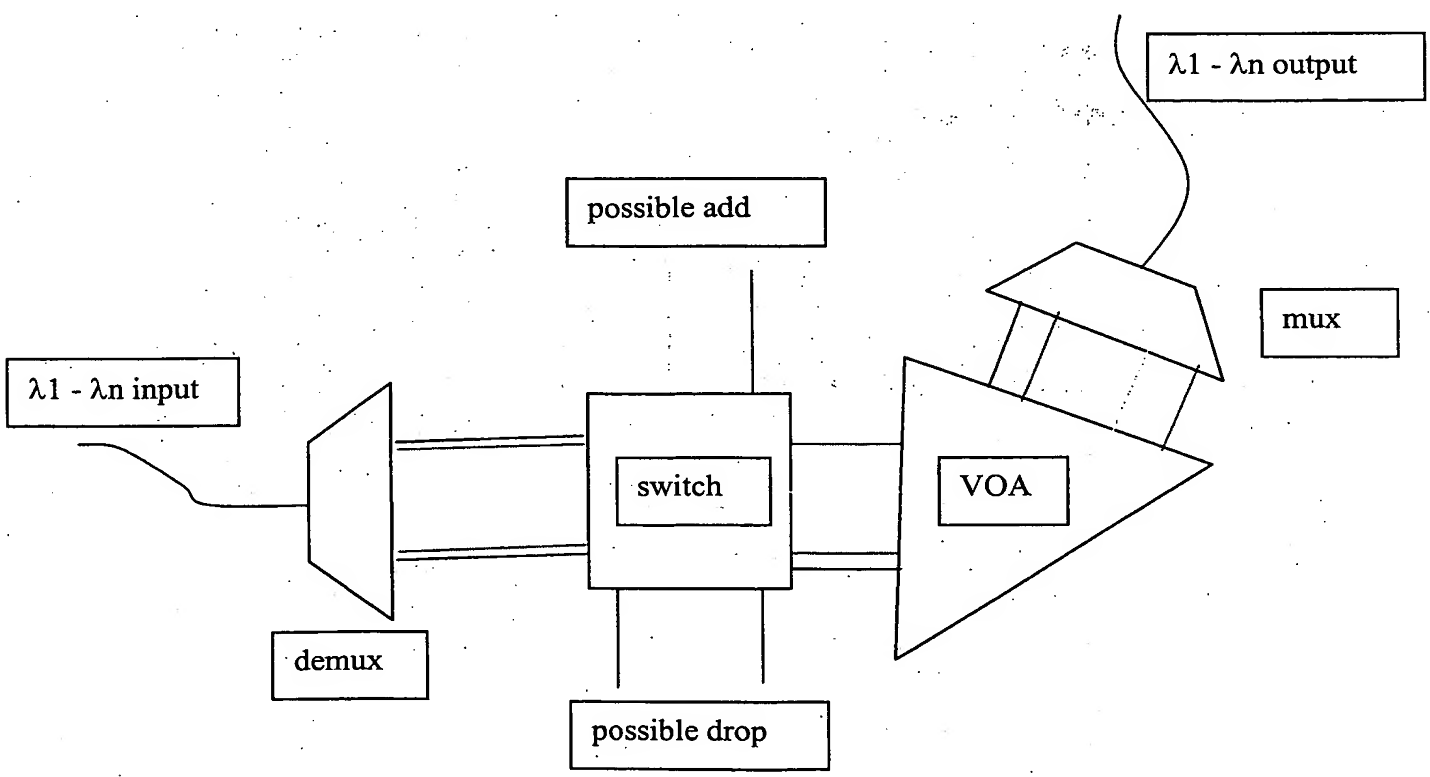


3.9.3. R-OADM – Reconfigurable Optical Add-Drop Multiplexer

Since the nature of the gel modulator is free-space, we see a possibility of doing a hybrid integration of multiple optical functions (mux/demux, switch array and VOA array) to build a R-OADM.

Our modulator does not have the scalability in terms of grating resolution in order to be the technology for the mux/demux function, but might integrate with another (free-space?) technology capable of delivering this feature. The switch array and the VOA array will be based on our technology, as described, maybe also considering monolithically integration of the VOA and switch function.

Rudimentary system sketch:



3.9.4. Monitoring devices

The diffraction principle is suitable for monitoring applications, e.g. by using one of the 1st orders as monitoring output, while the modulator also deliver some other optical function. Optical Channel Monitors (OCM's) may also be implemented by using calibrated detectors on the taps in the feedback system.

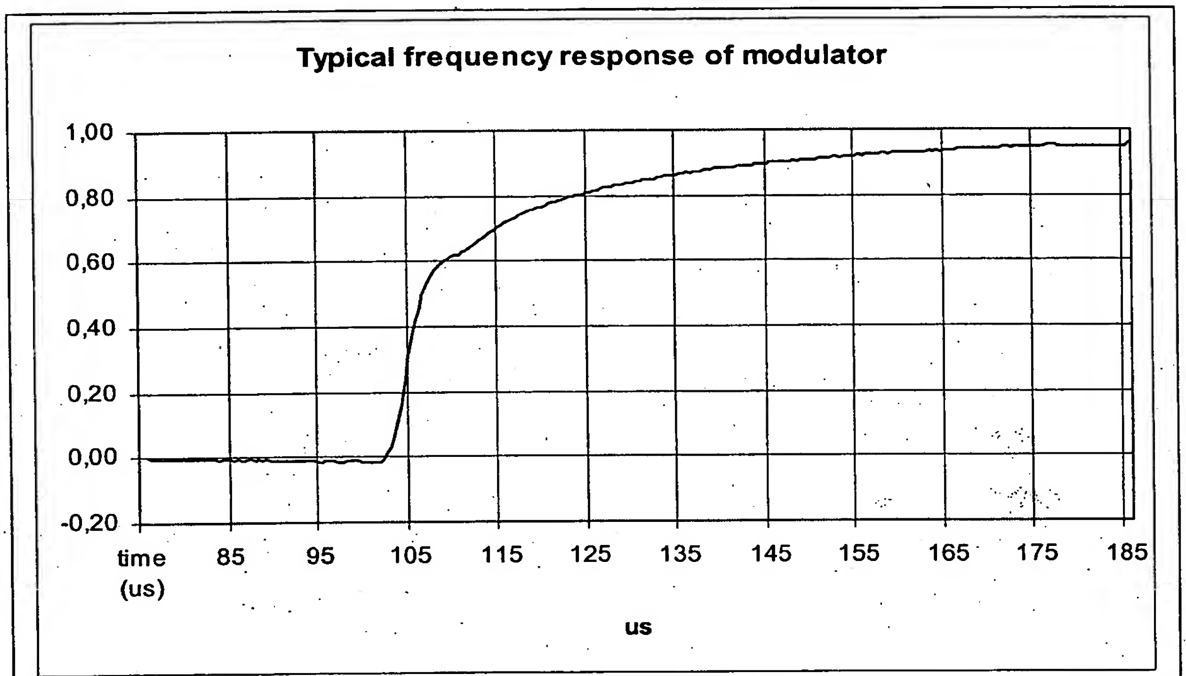
4. Appendix

4.1. The basic principles of running alternating mode (RAM) drive

This technical note describes the background of RAMDrive as a driving mechanism of the gel, and its principles of operation.

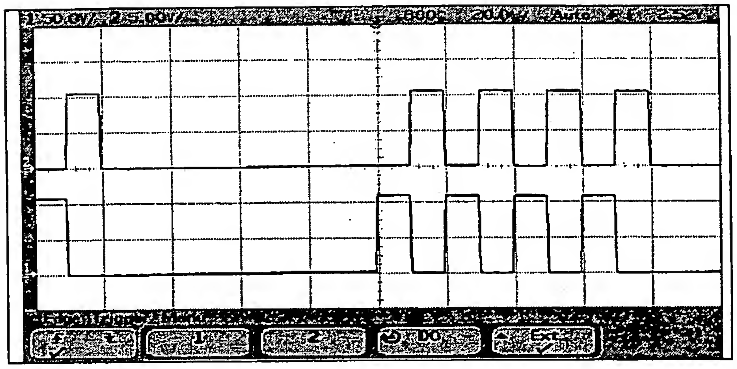
The slow charging process of the modulator may pose problems of possible applications in WDm systems. The RAM driving mode was introduced to reduce the effects when the modulator is left in the on position of a long time. However, the feedback system devised removed such difficulties.

The typical response of the modulator is shown below:

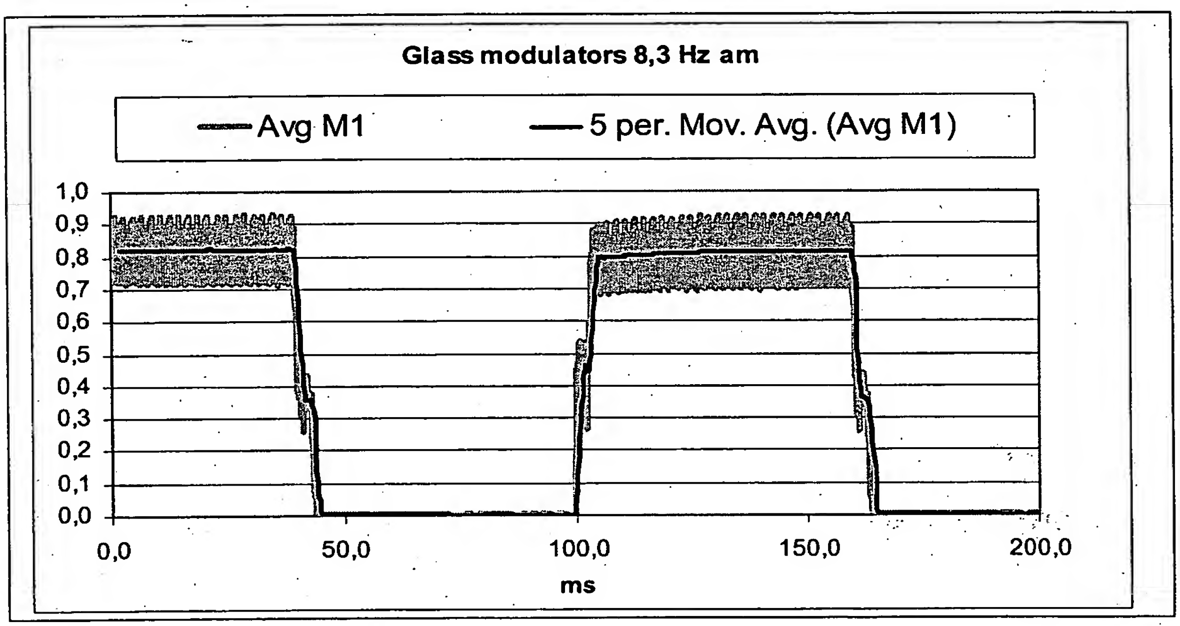


It is possible to optimise the "knee-point", but the slow charging after the knee-point will continue, resulting in a slowly increase in light intensity. In addition to the slow charging, when eventually switching off, the memory effect of the gel is considerable, and will not disappear quickly. This driving principle is call "Single-ended driving".

"Alternating mode" is a driving scheme which arouse in Russia when working with the projector system. It can take two forms, where the first one is basically just like single-ended driving, but the frames (projector talk again) are driven from the left and right side electrodes every second time. This is ok, as the frame frequency is relatively high, and no memory effect will take place. The second form is by driving left and right sides alternating during all ON-pulses, eg. as shown on plot below:



This mode will have a constant switching time, and may also be used for keeping the signal ON for a very long time. The typical response from the modulator to alternating mode is shown below:

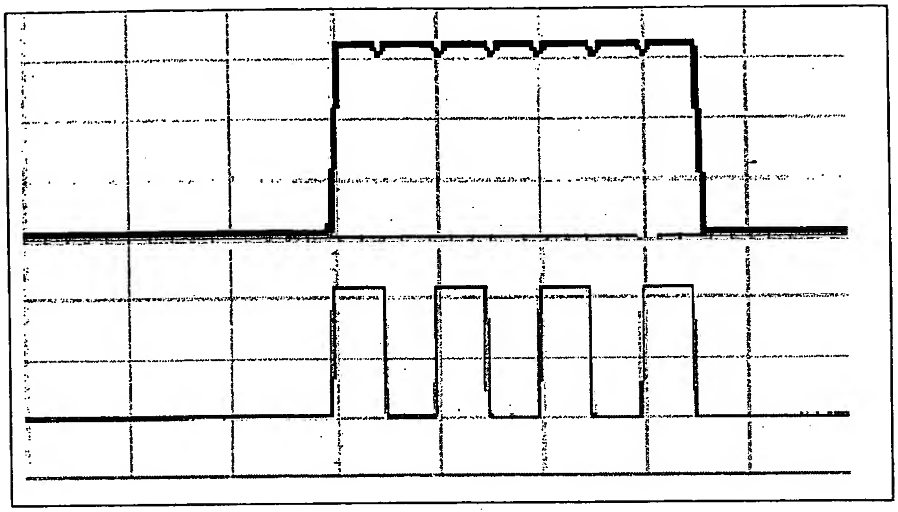


The black line is a slight integration of the signal, which is a good representation of what the human eye will perceive. This is hence ok for all visual systems. As can be seen on the actual signal, the switching frequency will affect the signal (or traffic), as the drive is removed from one side (gel relaxes) and then switched ON at the other side (gel relief is built up again). The gel modulation has physically moved. The whole grating will be shifted 180°. All these dips in the path of the traffic beam will probably make serious disturbance in many/most/all (not able to pick the exact word yet) telecom applications.

However, it is also quite clear that one traffic channel (fibre) will "look" at a set of lines, and not only one line pair forming 1 period. These line pairs may then not be alternated all at the same time, but one pair at the time. This is the basis of RAMDrive. Depending on the number of line pairs forming one traffic channel, the "dip" associated with each switching will be distributed over time. The noise introduced will depend on the following parameters:

- Number of lines used in one channel
- The transient characteristics of the gel
- The switching time (?)
- ... and there may be some more, but they are probably minor.

The general idea of the expected response is shown in the figure below:

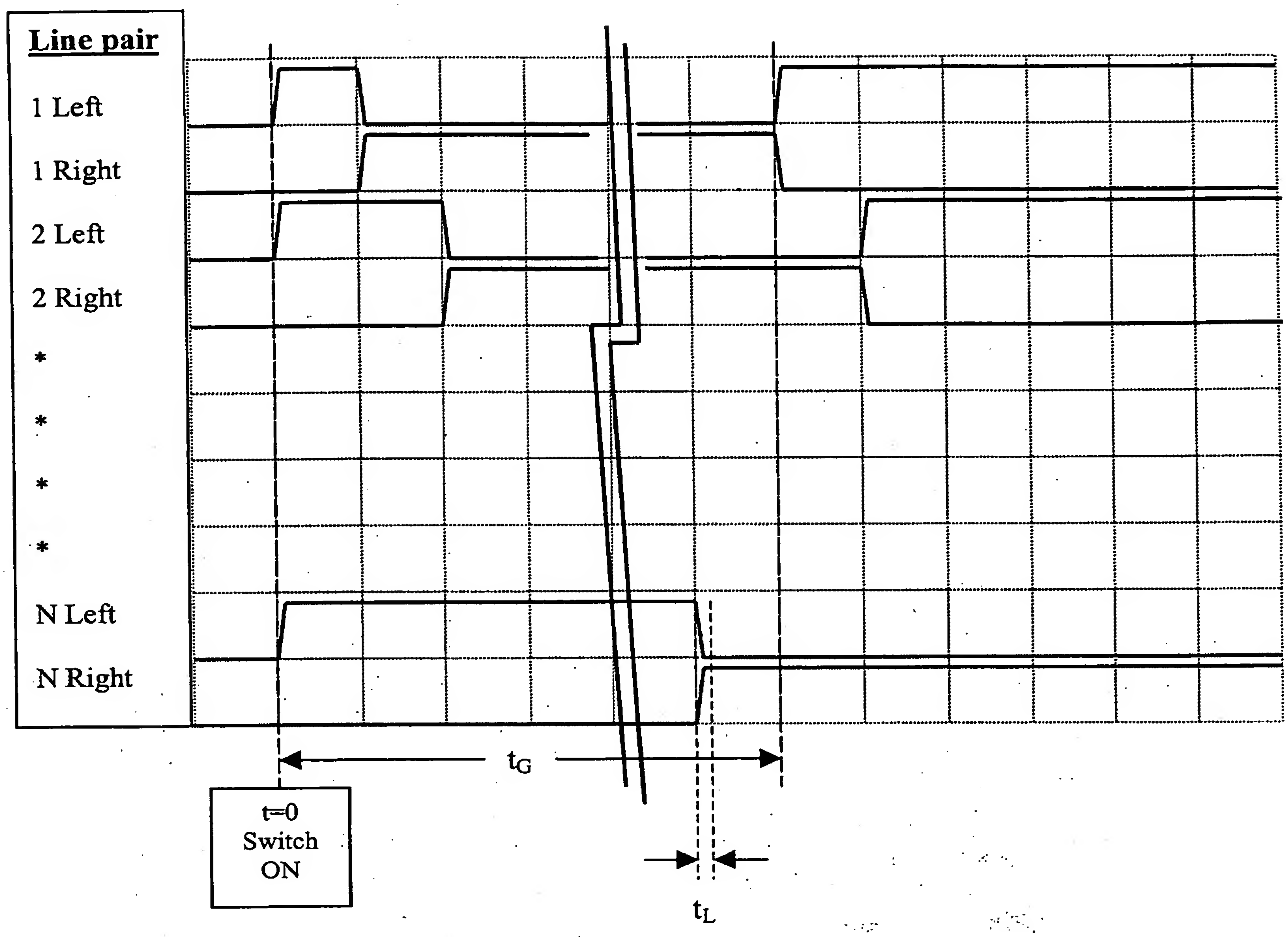


The lower pulse train indicates the switching of different line pairs, and the upper response indicates the expected behaviour. Note that this is just the general idea, and that no absolute values, ie. for S/N ratio, are given.

4.1.1. Principles of operation

One channel of traffic will make use of several line pairs of the modulator. The alternating mode is implemented by changing polarity of one line pair at the time. This makes only a relatively small part of the gel "flex" at anytime, minimizing the noise induced by the required alternating mode.

The figure below illustrates the driving logic:



The timing in the figure above is subject to optimisation, but it suggests that the polarity change of on line pairs is finished before the next line is addressed. It also suggests that all lines are switched ON initially, before the rolling starts. This is not strictly necessary, if the system requirement for switching time is significantly lower than the switching time of the gel (t_L). When the signal shall be switched OFF, all signals are grounded simultaneously (this is sort of natural), but not shown in the diagram above.

There are three parameters to optimise for achieving an acceptable S/N levels. These are:

- The number of line pairs, depends on substrate and optics
- The local switching time (t_L), depends on gel characteristics
- The global switching time (t_G), controlled by the driving logic

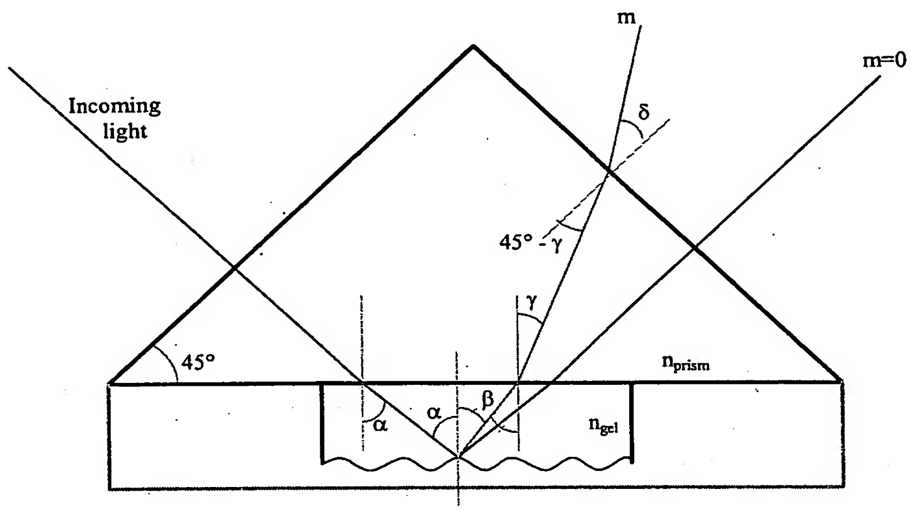
4.1.2. Discussions of the complexity of the driving scheme for applications

If comparing to the single-ended driving, where one voltage source can be used for all the lines forming one traffic channel, the driving scheme is a lot more complex, and requires many more driver channels. However, if alternating mode is the only alternative, the increase in complexity is

minimal. It requires the same amount of drivers, but adds some digital logic control, easily implemented in eg. an FPGA or a micro controller.

4.2. Output angles of diffracted beams

A description of the method to calculate the outgoing diffracted angles is provided below.



The incoming light enters the prism at normal incidence and propagates into to the prism in the same direction. When the light beam hits the bottom of the prism it will be partly reflected and partly refracted into the new medium, the gel. The refraction angle α is calculated by Snell's law:

$$\sin(\alpha) = \frac{n_{prism}}{n_{gel}} \sin(45°) \qquad (1)$$

Assuming almost matched refractive indexes for the glass (n_{prism}=1.45) and the gel (n_{gel}=1.40), reflection at the prism/gel interface can be neglected:

$$R_{||} = \left(\frac{n_{gel} \cdot \cos(45°) - n_{prism} \cdot \cos(\alpha)}{n_{gel} \cdot \cos(45°) + n_{prism} \cdot \cos(\alpha)} \right)^2 \quad \text{and} \quad R_{\perp} = \left(\frac{n_{prism} \cdot \cos(45°) - n_{gel} \cdot \cos(\alpha)}{n_{prism} \cdot \cos(45°) + n_{gel} \cdot \cos(\alpha)} \right)^2$$

leading to $\alpha \approx 47°$ and $R \approx 0.03\text{-}0.05\%$

Refraction and diffraction at each interface is considered in the following. Due to the numerous interfaces, no specific convention for the sign of each angle with respect to the normal of the interfaces was chosen. Instead, angles are always positive if not otherwise stated.

The modulated grating on the gel surface will then diffract the light. The incident angle is α and the angle for the m-diffraction order is β. β is given by the grating equation:

$$\sin(\beta) = \sin(\alpha) + \frac{m \cdot \lambda}{d \cdot n_{gel}} \qquad (2)$$

β is therefore dependent of the wavelength λ, period of the grating d, and the refractive index of the gel n_{gel}.

In the following, β is equal its absolute value.
The light is one more time refracted when it goes from the gel into the prism. Outgoing angle γ is given by:

$$\sin(\gamma) = \frac{n_{gel}}{n_{prism}} \sin(\beta) \qquad (3)$$

Equation (1), (2) and (3) can be put together to give:

$$\sin(\gamma) = \frac{m \cdot \lambda}{d \cdot n_{prism}} + \sin(45°)$$

Equation (4) shows that the angle is independent of the refractive index of the gel! The angle γ can be subsequently used to calculate the distance between the diffraction orders on the prism edge.

Finally, the angle separation δ between the 0- and the m-order outside the prism is given by :

$$\sin(\delta) = n_{prism} \cdot \sin(45° - \gamma)$$

4.3. How to make blazed gratings using a tuneable surface diffraction grating

It is desirable for some possible applications of tunable surface diffraction gratings in telecommunication areas to direct into an input optical fiber as much of diffracted light as it is possible. But actually there is a symmetrical distribution of an output light power in diffraction orders. For example, maximum intensities of light in ±1 diffraction orders are equal to 33.9% in the +1 order and 33.9% in the –1 order (for monochromatic light and harmonic relief on a gel layer surface). To obtain an asymmetrical distribution of light in diffraction orders, one can use an asymmetrical relief. One of possible shapes of the such relief is a saw-tooth profile. This technical note is devoted to a particular question: how to make a simplest saw-tooth relief with the use of a minimum number of electrodes.

4.3.1. Mathematical approach

The most primitive saw-tooth profile can be obtained as a sum of two harmonics as it follows from the formulas (1)-(3) and from Fig. 1 below.

$$F_\Sigma(x) = F_1(x) + F_2(x), \qquad (1)$$

$$F_1(x) = 100\cos\left(\frac{2 \cdot \pi}{16} x\right), \qquad (2)$$

$$F_2(x) = 25\cos\left(\frac{2 \cdot \pi}{8} x - \frac{\pi}{2}\right). \qquad (3)$$

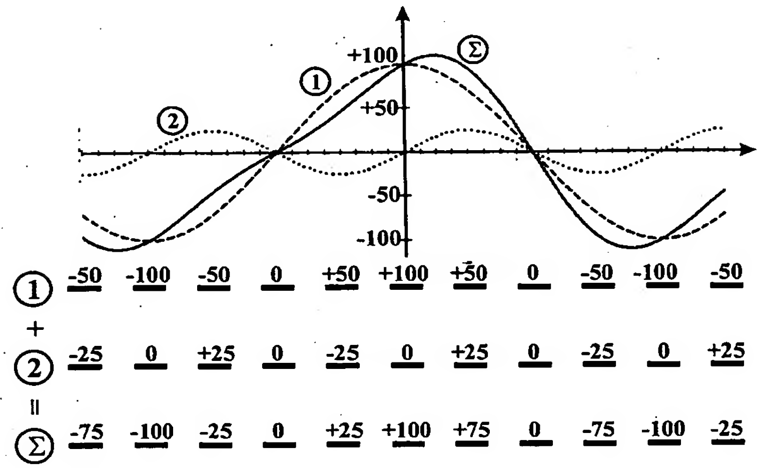


Fig. 1

If the amplitude of the second term $F_2(x)$ will be less then 20 or more then 30, it will result in not so nice saw-tooth shape as compared with Fig. 1. The same is valid for the phase shift of the second term: the value $\pi/2$ gives the most nice-looking saw-tooth profile.

4.3.2. Practical implementation

The saw-tooth profile (Fig. 1) of a potential distribution in the plane of electrodes can be obtained with the electrode structure shown in Fig. 1 under the plots. Bold dash lines symbolize linear electrodes and a value over each stroke is voltage applied to this electrodes. The upper line corresponds to the term $F_1(x)$, the middle line represents $F_2(x)$ and the bottom line is the sum $F_\Sigma(x)$.

It should be taken into consideration that the saw-tooth profile of a potential distribution in the plane of electrodes shown in Fig. 1 will not form a relief with the identical shape. The amplitudes of spatial harmonics of a potential distribution decrease from the plane of electrodes to the gel layer surface. And the rate of that decreasing is approximately two times higher for harmonic term $F_2(x)$ because it has two times larger spatial frequency (two times less spatial period). Also the amplitude of a harmonic relief caused by a harmonically distributed ponderomotive force decreases with increasing of spatial frequency (or, that is the same, with decreasing of spatial period) for a constant amplitude of the force.

Because of this the amplitude of the first spatial harmonic of a relief $A_1(x)$ (caused by the first spatial harmonic $F_1(x)$ of a potential) will be not 100/25=4 times but, for example, 6-8 times larger comparing with the amplitude of the second spatial harmonic $A_2(x)$ (caused by $F_2(x)$). And the sum $A_1(x)+A_2(x)$ will have not so nice saw-tooth shape as compared with the sum $F_1(x)+F_2(x)$.

To compensate a higher rate of decreasing of the amplitude of $F_2(x)$, one should use larger amplitude for $F_2(x)$. It will correspond to not very nice saw-tooth shape of the potential distribution in the plane of electrodes but to a "normal" (Fig. 1) saw-tooth shape of a relief.

It should be taken into consideration that a saw-tooth profile of a relief on a gel layer surface in the tuneable surface diffration grating can not be very sharp. Particularly, it is impossible for real practical parameters to make a saw-tooth relief with the top angle 90^0 (Fig. 2). The main reason is that typical achievable amplitudes of a relief are equal to **A~0.1-0.2 μm**. And typical spatial periods of a periodical relief are equal to **d~10-50 μm >>A.**

One can assume that for the such values of **A** and **d** it might be possible to achieve a relief with the 90^0 top angle as it is shown in Fig. 3. But it is also non-realistic because of strong damping of a relief by surface tension for very high angles of a relief to a horizontal (the angle **β** in Fig. 3 is also ~ 90^0).

A realistic saw-tooth profile that can be achieved on a gel layer surface is shown in Fig. 4. The top angle here is close to 180^0 because of typically small values of angles of lateral sides of a relief protrusion to a horizontal.

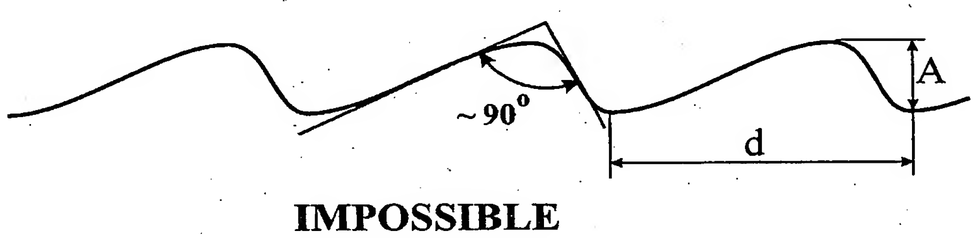


Fig. 2

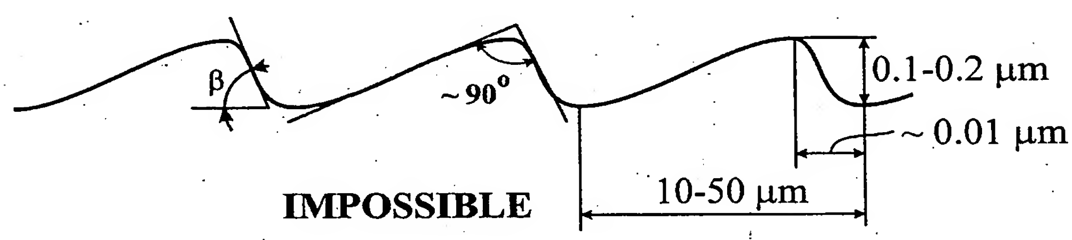


Fig. 3

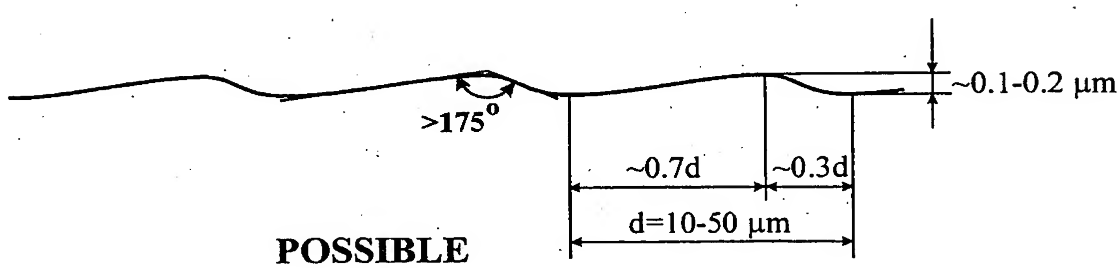


Fig. 4